INTEGRATED ANALYSES OF TECHNO-ECONOMIC AND ENVIRONMENTAL EFFICIENCIES OF HOM MALI RICE CROPPING SYSTEMS IN THAILAND

by

Kwansirinapa Thanawong

A dissertation submitted in partial fulfillment of the requirements for
the degree of Doctor of Engineering in
Water Engineering and Management

Examination Committee:	Dr. Sylvain R. Perret (Chairperson) Prof. Mukand S. Babel (Co-chairperson) Dr. Peeyush Soni (Member) Dr. Roberto S. Clemente (Member) Dr. Rattanawan Mungkung (External Expert)
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ABSTRACT

Rice is the world’s most important staple food crop with more than half of the world’s population relying on it as the major daily source of calories, especially in Asia. Paddy rice grows throughout Thailand, but the main production areas are in Northeast of Thailand, followed by North region, Central Plains and South region. Among the many varieties of rice grown in paddy areas; Kao Dok Mali 105 variety (Hom Mali rice, or jasmine-scented rice) is a high quality fragrant rice, exported to Europe and the USA.

While rice production creates food security, employment and growth, it also generates adverse environmental impacts and resource consumption. Nowadays, consumers’ environmental awareness is rising and rice production systems require more sustainable management practices. It has been hypothesized that both objectives of high economic return and low environmental impacts of rice production systems might not be fully met simultaneously, and that trade-offs are inescapable, towards sustainable yet profitable farming practices. Balanced agricultural systems have to be identified, and the economic viability of environment-friendly practices at the farm level has to be investigated.

This research has investigated the environmental impacts and the techno-economic performances of selected rice farms in Nam Mae Lao basin (North region) and Lam Sieo Yai basin (Northeast region). Paddy areas under rain-fed and irrigated conditions, in wet and dry seasons were studied.

This research compares the advantages of rice production under irrigation and rain-fed conditions in both environmental and economic terms. Indicators of techno-economic performances were combined with environmental impact indicators based upon life cycle assessment, energy and water use analyses. Data were collected in 2010 at the farm level in 60 households for both study areas, according to three cropping systems, namely wet-season rain-fed (Rw), wet-season irrigated (Iw) and dry-season irrigated (Id) systems. Eco-efficiency indicators were calculated as per impact category. Technical and environmental efficiencies were calculated for both selected basins by using a combination of techno-economic analysis, LCA results and Data Envelopment Analysis (DEA) methodology. DEA approach, particularly allowed to identify the sources of technical and environmental inefficiencies within the systems.

The research collected, analyzed and combined indicators of techno-economic performances (rice production, costs, and product value) with environmental impact indicators based upon the life cycle approach. Both approaches applied at the same plot level (cropping system level). Techno-economic analysis typically resulted in monetary values as per factor of production (e.g. labour, land, agro-chemicals). LCA expressed environmental impacts as per selected functional units (mass of product and area of land used). The research reported here is problem-oriented; it focuses on midpoint indicators for different environmental impact categories (e.g., global warming potential, eutrophication, or acidification) and resource use (land, water and energy). LCA methodology can assess such environmental impact categories, but it still does not include methods for assessing the impact of water use at river basin level. Such impacts have been investigated through the application of the water footprint methodology. Blue water and green water were assessed through Crop and Irrigation Water Requirement concepts (CWR, IWR respectively).

Both basins show wide-ranging techno-economic performances and environmental impacts, while cropping practices were found to be homogeneous. Differentiation of systems originated mostly from differences in yield, which were mostly impacted by water supply.

North region produces higher yields than Northeast region; yields in Nam Mae Lao basin vary from 3,594, 3,258 and 3,438 kg/ha, yield in Lam Sieo Yai basin are 2,625, 2,375 and 2,188 kg/ha in the Iw, Rw and Id systems, respectively.

The results highlight the low performances of Id systems in both techno-economic and environmental terms. Id systems require mostly blue water, while the two other systems rely primarily on green water. Id systems also require more energy and labour, due to increased water management needs. Overall, the productivity of most production factors in Nam Mae Lao basin was found to be higher in irrigated systems; these results in return on investment being higher in the Iw systems compared to the Id systems (0.174 kg/THB and 0.162 kg/THB, respectively) and is lowest in the Rw systems (0.154 kg/THB), on the hand, the productivity of most production factors in Lam Sieo Yai basin was found to be higher in Rw and Iw systems which results in return on investment being slightly higher in the Iw systems compared to the Rw systems (0.117 kg/THB and 0.114 kg/THB, respectively) and is lowest in the Id systems (0.095 kg/THB). In northeast region, in Id systems, farmers need to produce twice as much rice (0.411 kg) to obtain 1 THB of net income, compared to 0.228 and 0.248 kg for Iw and Rw respectively. Northern regions to obtain 1 THB of net income, farmers in Rw need to produce 0.20 kg compared to 0.173 and 0.185 kg for Iw and Id.

Lam Sieo Yai basin, emissions proved relatively similar across all three systems of selected basins, with the exception of CH_4, which was markedly lower in Rw systems due to specific water and organic residue management. Id systems systematically emitted more nitrates, phosphates and pesticides into water sources. Rw systems showed the lowest environmental impacts per ha and per kg of paddy rice produced. GWP_{100} was higher in Id systems (5.55 kg CO_2-eq per kg of rice) compared to Iw (4.87) and Rw (2.97). In Nam Mae Lao basin, emissions proved relatively similar across all 3 systems of selected basins, with the exception of CH_4, which is lower in Id systems. Id also showed the lowest environmental impacts per ha and per kg of paddy rice produced due to higher yields. GWP_{100} was higher in Iw systems (2.90 kg CO_2-eq per kg of rice) compared to Rw (2.24) and Id (2.15).

This research also addressed the water deprivation potential resulting from water use and the water stress index of each selected basin. The total water use of Nam Mae Lao and Lam Sieo Yai basin are 2,650 and 2,948 Mm^3/year, respectively, while the annually available water in basins are 4,301 and 2,483 Mm^3/year. WSI were 0.86 in Nam Mae Lao basin, and 1.00 in Lam Sieo Yai , which indicate a higher potential for water deprivation in the northeast region.

Lam Sieo Yai basin, Rw systems were found to be more eco-efficient in most impact categories, including Global Warming Potential. The total value product per kg of CO2-eq emitted is 4, 2.5 and 2.2 THB in Rw, Iw, and Id systems respectively. Nam Mae Lao basin, Id systems were found to be more eco-efficient in Global Warming Potential but lowest in other impact categories. Environmental efficiency of Nam Mae Lao basin were found to be higher in Rw system, followed by Id and Iw systems, but Id system has more environmentally efficient in Lam Sieo Yai basin and followed by Rw and Iw systems.

Finally, DEA analysis allowed identifying and quantifying the potential increase of technical performances and the potential reduction of environmental impacts of each rice cropping system, based upon the most efficient systems as references. In terms of technical efficiency, both basins converge and show that Id systems have the least efficient. VSR and CSR based efficiency scores are very different, resulting in scale efficiency scores that are low overall. This pinpoints the fact that rice systems operate mostly at increasing return on inputs, which suggests that critical inputs, such as N fertilization, are still not used optimally. In terms of environmental efficiency, both basins also converge to show that Rw systems are the most environmentally efficient, and that Id systems are the worst. Further analyses at DMU level demonstrate the poor overlapping between high-income and low environmental impact sub-groups. Further, high income does not link up with low production costs. These findings highlight the need for trade-off towards sustainability. Rice cropping systems shall optimize inputs and resource use, in order to have lesser environmental impacts. Finally, ranges of potential reductions in input supply are calculated, for systems to achieve full technical efficiency.

Final sections of the report discuss the methodological, scientific and societal contributions of the research, and provides some specific recommendations.

TABLE OF CONTENT

TABLE OF CONTENT (Cont'd)

TABLE OF CONTENT (Cont'd)

TITLE **PAGE**

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF TABLES (Cont'd)

Table No. Title **PAGE**

LIST OF FIGURES

Figure No. Title **PAGE**

LIST OF FIGURES (Cont'd)

Figure No. Title **PAGE**

LIST OF ACRONYMS

AP	Acidification Potential
CWR	Crop Water Requirement
CRS	Constant Return to Scale
CFOA	Conversion factor for as organic amendment
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
EE_{CRS}	Environmental efficiency by CRS
EE_{VRS}	Environmental efficiency by VRS
EP	Eutrophication Potential
ETa	Actual Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration
FAETP	Freshwater aquatic ecotoxicity potential
FAO	Food and Agriculture Organization of the United Nations
FEU	Fossil energy use
FU	Functional Unit
GAP	Good Agricultural Practices
GHG	Green House Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IWR	Irrigation Water Requirement
Kc	crop coefficient
LCA	Life cycle assessment
LCI	life cycle inventory
LCIA	Life Cycle Impact Assessment
LDD	Land Development Department
MOAC	Ministry of Agriculture and Cooperatives
NDRS	non-decreasing return to scale
NIRS	non-increasing return to scale
ODP	Ozone Depletion Potential
RID	Royal Irrigation Department
ROA	Application rate of organic amendment
SCE	Scale efficiency
SFp	CH_4 emission scaling factors for water regime before cultivation (pre-season)
SFw	CH_4 emission scaling factors for water regime during cultivation
SRF	Strongly regulated flows
TE_{CRS}	Technical efficiency by CRS
TE_{VRS}	Technical efficiency by VRS
TMD	Thailand Meteorology Department
USDA	United States Department of Agriculture
VF	variation factor
VRS	Variable Return to Scale
VW	virtual water
WSI	Water Stress Index
WTA	withdrawal-to-availability
WU	Water Use
WU_b	blue water use

LIST OF ACRONYMS (Cont’d)

WU_g	green water use
WU_{gr}	grey water use
WDP	Water Deprivation Potential

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Rice (Oryza sativa L.) feeds more than 3 billion people globally. Approximately 75% of the 150 million ha harvested worldwide are irrigated and provide food, income, and a diversity of ecosystem goods and services (Bouman et al., 2007a; 2007b), yet they also have negative impacts on the environment (Roger et Joulian, 1998; Tilman et al., 2001; Wenjun et al., 2006). Rice production requires large amounts of resources (water, land, energy, and chemicals), and contributes to pollution in all environmental compartments, including water and the atmosphere, due to quasi-permanently flooded (ponding) conditions. Flooded rice grows under anaerobic conditions, which favour methane formation and release. Approximately 120 g of CH4 are released into the atmosphere for each kg of rice produced; overall, the world's rice cropping under flooded conditions contributes 13% of all anthropogenic CH_4 emissions (IPCC, 2006).

Thailand is the world's 6th largest rice producer and largest exporter. In recent years, annual paddy output has been approximately 30 Mt, with a third being exported. Rice is grown on some 10 million ha of land (or 20% of the country), with more than half grown in the Northeastern region (Isaan), the poorest region of the country. Approximately 9% of Thailand's population still lives under the poverty line; most of this population consists of subsistence-oriented, seasonal rice growers in the Isaan who sell production surplus and rely on multiple income sources for their livelihoods. Also, increasing scarcity of farm labour afflicts the region (ADB, 2012).

As a consequence, any attempt to reduce the environmental impact of rice production (through input reduction or alternative water management) or to develop irrigation should take into account the consequences with respect to economic performances such as changing yields, changing farmer income and higher labour requirements. In addition, in view of plans to extend irrigation in Isaan (Molle and Floch, 2008), there is a need to assess the comparative advantages of controlled irrigation vs. rain-fed cropping (uncontrolled irrigation during the wet season) in both environmental and economic terms.

As mentioned above, to grow rice, freshwater is needed mostly to control weeds. It is the most important resources for humans as well as for anthropogenic and natural ecosystems. Available water is becoming scarce, with increased demands and competition between users, including the environment. Freshwater forms the portion of water resources suitable for use by humans and most of the terrestrial vegetation and wildlife, it is a renewable resource supplied by rainfall and surface runoff, and used as surface water, groundwater, and water retained by soil (UNEP, 2008). Freshwater use measurements provide information about the impact due to withdrawal by different users such as manufacturing and production of goods and services. In this report, only freshwater use for rice production is addressed. Freshwater use for rice production can be divided into two forms of demand, which including blue water use (water evaporated by irrigated crops, land and systems) and green water use (water evaporated by rainfed crops and land). Water enters an ecosystem in the form of precipitation, and leaves through evaporation and evapotranspiration by the plant.

Paddy rice production is contributing to climate change, and is harmful to the environment when conducted with high inputs (Neue, 1993; Roger et Joulian, 1998; Tilman et al., 2001; Wenjun et al., 2006). International and Thai research organizations have recently initiated LCA-based characterization of agricultural products, such as rice. As shown in chapter 2, literature review section, many studies addressed the typical conventional rice production and processing system. When alternatives are compared, they concern post-harvest system. Interestingly, all these studies also acknowledge that crop production generates most of environmental impact. Impact categories remain also typically limited to energy use, abiotic depletion, global warming potential, acidification and eutrophication. It features also a high water requirement about 80% of freshwater abstractions in Thailand contribute to rice production systems; pesticide related toxicity is becoming a major concern. Yet, no integrated research has so far addressed those impact categories, namely freshwater use, water resource depletion and toxicity. Therefore, this research was focused onto rice production systems which carry out cradle-to-farm gate, taking into account a diversity of production condition and practices and considering typical indicators and also indicators on freshwater use and water resource depletion at local or basin level.

Nowadays, rice production system calls for more sustainable management practices. However, the economic viability of environment-friendly practices (high economic return and low environmental impacts) at the farm level is also a concern. In Thailand, we have the Office of Agricultural Economics, Ministry of Agriculture and Cooperative which every year, publishes the survey’s report of rice. Normally, the report mentions about cultivation area of paddy rice, total production and yield of rice and total fertilizers use in the paddy field but lack of all the techno-economic performance, such as land use productivity, energy use productivity, labor productivity, water crop productivity, irrigation water productivity, all the input productivity (Fertilizer, pesticide, other chemical use), cropping intensity, production cost and net return to production which those techno-economic and environmental indicators are need to balance between economic return and environmental impact to come up with environment-friendly practices. Therefore, this present research undertakes to investigate economic return including all the inputs use and environmental impact of selected rice systems.

1.2 Problem statement

Rice cropping does not only produce food but also generates wealth and jobs, provides monetary resources to millions in rural areas of developing countries, especially in Asia. It also creates environmental impacts that some believe to be unacceptably high (Tilman et al., 2001; Wenjun et al., 2006). Apart from soil and water pollution, and consumption of energy, water and raw materials, paddy fields (irrigated or flooded land used for growing rice) are in fact claimed to be responsible for 10 to 15% of worldwide methane anthropogenic emissions (Neue, 1997), thus contributing to a great extent to the global warming phenomenon. Many of the environmental problems are caused by each process of producing rice, for example, using fertilizers is increasing pollution in aquatic ecosystems. For these reasons, and as environmental awareness increases, it becomes crucial to understand and manage the environmental impacts of rice production, including not only the industries and business sectors but also agricultural sector. Society has become concerned about the issues of natural resource depletion and environmental degradation. Quality fragrant rice is also now massively produced by Vietnam and Myanmar for export. In order to keep its leading position, Thailand has to improve the production systems with lower environmental impacts. Ministry of Agriculture and Cooperatives of Thailand established "Good Agricultural Practices (GAP) for Rice" as agricultural standards towards environmental-friendly and consumer-friendly practices. The establishment of such standards is important to significantly promote and encourage quality and safety in rice production, in order to be accepted for both domestic and international trade. Thai GAP also includes specific measures in order to reduce methane emissions from the fields: low-methane gas from alternative rice cultivars, direct seeding, soil aeration with water management, organic matter and fertilizer management.

LCA was applied to many products since 1990s, but there is still no comprehensive research on rice done in Thailand, including taking account of the diversity of systems and the whole production chain of rice.

A special focus is put on Hom mali rice in this research, as it is the top quality export rice of Thailand, exported in Europe, where eco-labeling of agrifood products is gaining interest and momentum, and will soon require LCA-based assessment of environmental impact indicators (Basset-Mens et al, 2010). For instance France established compulsory carbon-footprint eco-labelling of retail agrifood product by July 2011, first on pilot products (including rice), then on all, with probable inclusion of other indicators in close future. That is another reason for doing the research, focusing on Hom Mali rice, but also by comparison with other varieties of rice. Finally, as mentioned above, water resource use is a key feature of paddy rice production; question remains as to how does it impacts on overall water availability and regional resource depletion; some initial work has been done internationally (Pfister et al., 2009; Mila i Canals et al., 2009), and also locally (Rahatwal, 2010), but there is a need to finally fix the methodology, and provide some case studies from different places in Thailand.

As mentioned in the previous section, authorities recognize the need to develop more sustainable, environmental-friendly rice cropping systems, and yet, any attempt to reduce environmental impacts must consider its possible negative feedbacks on yields and production costs. Such rice-poverty-food-environment knot requires research on the interactions between rice production performances and environmental impacts, and possible trade-offs between them. Also, the diversity of actual cropping systems and their respective techno-economic performances and environmental impacts is not well documented

1.3 Research questions

The problem statement leads to the following research and societal questions:

1) What are the main Hom Mali fragrant rice cropping systems of, in the main production areas of Thailand, i.e. the North and Northeast regions?
2) What are the technical and economic performances of these systems, taking into account their diversity at the farm level?
3) What are their environmental impacts?
4) Can jasmine rice systems be both techno-economically sound and environmental friendly? Or are trade-offs inescapable?
5) Can one identify the cropping systems that best combine high outputs (production), low production costs and low environmental impacts?

1.4 Objectives of the study

The main objective of the study is to investigate together techno-economic performances and environmental impacts in selected Hom Mali rice cropping systems, in order to identify more efficient and sustainable practices.

The specific objectives of the studies are:

1) To identify and describe diverse typical Hom Mali rice cropping systems in selected basins in Thailand,
2) To analyze techno-economic performances using technical and economic analyses,
3) To assess potential environmental impacts, including pollutions and resources use from LCA perspective, with a focus on water resource depletion as an impact category,
4) To investigate the relationship between techno-economic performances, resource use and potential environmental impacts from efficiency, trade-off and optimization perspectives,
5) To identify best practices towards more sustainable and efficient Hom Mali rice cropping systems, and to draw recommendations.

1.5 Scopes and limitations of the study

The scopes and limitations of the study spans as follows:

1) The basic unit for the research is the paddy field under cultivation for a given season, managed by a farmer. It is defined as a Decision Making Unit DMU. Data were collected at that system level through direct observation, farmer interview through structured questionnaire, and secondary sources.
2) One year data (2010) were collected.
3) The number of rice cropping systems to be studied (DMUs as samples) shall be sufficient to allow for analysis, but realistically limited to the timeframe and resources. Total sampling of 120 DMUs was ultimately studied.
4) Such cropping systems and related farms are studied in two main areas: North East of Thailand (Lam Sieo Yai basin) and North of Thailand (Mae Nam Lao basin)
5) Such cropping systems were primarily under Hom Mali rice rainfed and irrigated conditions
6) Techno-economic performances are assessed at the DMU level
7) Techno-economic performances include production and production factors: land, water, labor, inputs (fertilizer and pesticide), energy, gross income, net income and production costs
8) To estimate water used by rice at field level, water balance principles and concepts are used (e.g. Crop Water Requirement -CWR- and Irrigation Water Requirement -IWR- concepts, and related methodology tools -CROPWAT-).
9) Partial Life Cycle Assessment approach is applied to all DMUs; the system under consideration is limited to production, i.e. to the farm gate; functional units refer to the impact as per farm gate product (mass unit of rice), and as per different production factors (inputs, resources),
10) SimaPro model is used as a tool to calculate environmental impact indicators.
11) Impact categories include global warming potential, eutrophication, acidification, freshwater aquatic ecotoxicity, ozone depletion and resource depletion, especially water, land use and energy use

12) The calculation of eco-efficiency is the ratio of economic value and the environmental impacts which provide eco-efficiency as per environmental impact category
13) To investigate the relationship between techno-economic performances, resource use and potential environmental impact from trade-off and optimization perspectives, Data Envelopment Analysis (DEA) is used to optimize from non-parametric relationships
14) Technical and environmental efficiency indicators were calculated as per farming system
15) Technical and environmental efficiency indicators are the revealing of the gap between frontier efficiency and actual efficiency of systems with regards to techno-economic performances and environmental performances, respectively.

1.6 Outline of the dissertation

Chapter 1 is the introduction of this thesis. Chapter 2 includes the literature review and state of the art. Chapter 3 presents the study areas, which are Nam Mae Lao (North region) and Lam Sieo Yai (Northeast region) basins. Chapter 4 describes the methodology adopted for the research. Chapters 5 to 9 include the results, and discussions thereof, meeting the research objectives. Chapter 10 presents the conclusions and recommendations of the research.

CHAPTER 2

LITERATURE REVIEW AND STATE OF THE ART

2.1 Rice production in Thailand

Thai jasmine rice is also known as 'Thai Hom Mali rice' as well as 'Thai Jasmine Rice' and 'Thai Fragrance Rice' which is the long grain rice which is well known for its fragrance and taste all around the world. Thai jasmine rice is one of the main export products of Thailand. Because of the most suitable geographic location, Thailand can grow the best quality and unique jasmine rice. Thailand has 5000 years agricultural history, which is also the pride of Thai Jasmine Rice's history. In 1945, Kao Dok Mali (KDML) was discovered in Chonburi province. KDML is also known as 'White Jasmine' in Thai language. Ministry of Agriculture started to select and carry out experiments with this species of KDML rice in Lopburi province, and try to grow the selected rice in the northern and north eastern part of Thailand. On 25th May 1959, it was officially announced that this species of rice would be named 'Thai Hom Mali Rice' (or KDML 105), which also one of the most important consuming products in Thailand. Until recent day, there are KDML 105 and RD 15 in Thailand.

Thailand is the world's 6th the largest rice producer and largest exporter. In recent years, annual paddy output has been approximately 30 Mt, with a third being exported. Rice is grown on some 10 million ha of land (or 20% of the country), with more than half grown in the Northeastern region (Isaan), the poorest region of the country which the best quality Thai Jasmine Rice are grown mainly in the north eastern provinces such as Roi Et, Ubon Ratchathani, Burirum, Sisaket, Surin and Yasothon. Approximately 9% of Thailand's population still lives below the poverty line; most of this population consists of subsistence-oriented, seasonal rice growers in the Isaan who sells production surplus and rely on multiple income sources for their livelihoods. Also, increasing scarcity of farm labour afflicts the region (ADB, 2012). More than 80 percent of the rice growing area in Thailand is under rainfed conditions where rice is usually grown only once a year in the wet season, where the monsoon rain is the single source of water supply for rice cultivation. Rainfed conditions refer to the uncontrolled supply of water to paddy fields, where water is kept for rice cropping by controlled drainage. Less than 20 percent of the area is under irrigated conditions where rice can be grown not only in the wet season, but also in the dry season when irrigation water supply is available (Kupkanchanakul, 2000). Irrigation refers to the purposive, organized, infrastructure-supported supply of water to paddy fields, with controlled drainage. Rice production in Isaan is mostly lowland rainfed (75%) and shows low yields (2.5t/ha). The Central Plain area is mostly irrigated (80%) and shows more intensified production patterns, with higher yields (3.5t/ha), yet far from regional records of more than 4 in Vietnam or China. Thailand's lower yields also refer to the choice of growing low-yielding, high quality, high value varieties (Jasmine rice for domestic and export use).

Rice is the world's most important staple food crop with more than half of the world's population relying on it as the major daily source of calories and protein (Kasmaprapruet et al., 2009). Since 1960, rice consumption still increased regularly as shown in Figure 2.1. Rice production is the main agricultural production of Thailand. The total agricultural area is 21.20 million ha (M-ha) and around 11.20 M-ha (53% of agricultural area) is covered by paddy fields, although with seasonal variations (Chuvisitkul, Thai Research and Development, 2008). According to the survey report by the Office of Agricultural Economics (OAE, 2008), in wet season, 9.19 M-ha are under rice cultivation, with a production of 23.235 million tons (MT); in dry season, 2.05 M-ha produce 8.791 MT. The amount of paddy rice in one year is around 32 MT and 45%, 5%, 10% and 40% of paddy rice is used for consumption in the country, seeds for the next year, industry purpose and export to the world market, respectively. Thailand is only the fifth world largest rice producers, but has long been the largest exporter with almost 8MT exported in 2009. Thailand mostly exports white rice (5.4Mt in 2009; by Government and private exporters) and Hom Mali rice (2.4Mt in 2009; only by private exporters). Thailand exports rice to many countries, including European countries. Figure 2.2 shows the amount of import of rice in Europe, which has increased since 1961 and keeps increasing.

Thailand is the first exporter of rice in the world, followed by Vietnam, but paddy rice productivity (yield) remains low (2.65 ton/ha), lower than the world average yield (5 ton/ha) and Vietnam average yield (4.48 ton/ha). In Thailand, typical rice plots are usually small (less than one ha per family) and cropped by poor, small-scale peasant farmers. Yet, production systems and cropping practices vary significantly. Some irrigation systems along main rivers in the central plain of the country show intensive production, mechanization, high use of pesticides and fertilizers while North-Eastern areas are much poorer, with more traditional, manual, cropping systems (some being only based upon wet season / rain-fed rice).

Paddy rice grows throughout Thailand, but the main production areas are in Northeast of Thailand, which represents around 56% of the total cultivated rice area in Thailand, followed by the North region (22%), central plain (17%) and south region (5%). In Thailand, there are many varieties of rice grown in paddy areas; Kao Dok Mali 105 variety (Hom Mali rice, or jasmine-scented rice) is the most popular rice exported to Europe and the USA. White rice is exported to Africa and the Middle East.

Thai Hom Mali Rice enjoys an international reputation for its aroma and the texture which is tender and versatile to blend effectively with a wide variety of dishes. Grown only in Thailand, Thai Hom Mali Rice is the world's only indigenous rice with a natural fragrance. Hom Mali, generally known as "Fragrant Jasmine Rice" or "Jasmine-scented rice", grown in Thailand has a quality that its variety grown in other parts of the world does not have. Kao Dok Mali 105 is rainfed, photo-sensitivity variety of rice, flowering around 20-25 October. Its production in north-eastern part of Thailand is relatively low due to low soil fertility and uncertainty of rain. For more production, application of organic fertilizer is recommended. It was found that Kao Dok Mali 105’s aroma correlates to soil qualities, especially Roi Et, Kula Ronghai, Ta Tum in Surin. Hom Mali rice, is also growing in other area in Thailand such as in Northern part of Thailand, but its quality of rice is lower than Hom Mali rice in the northeast region.

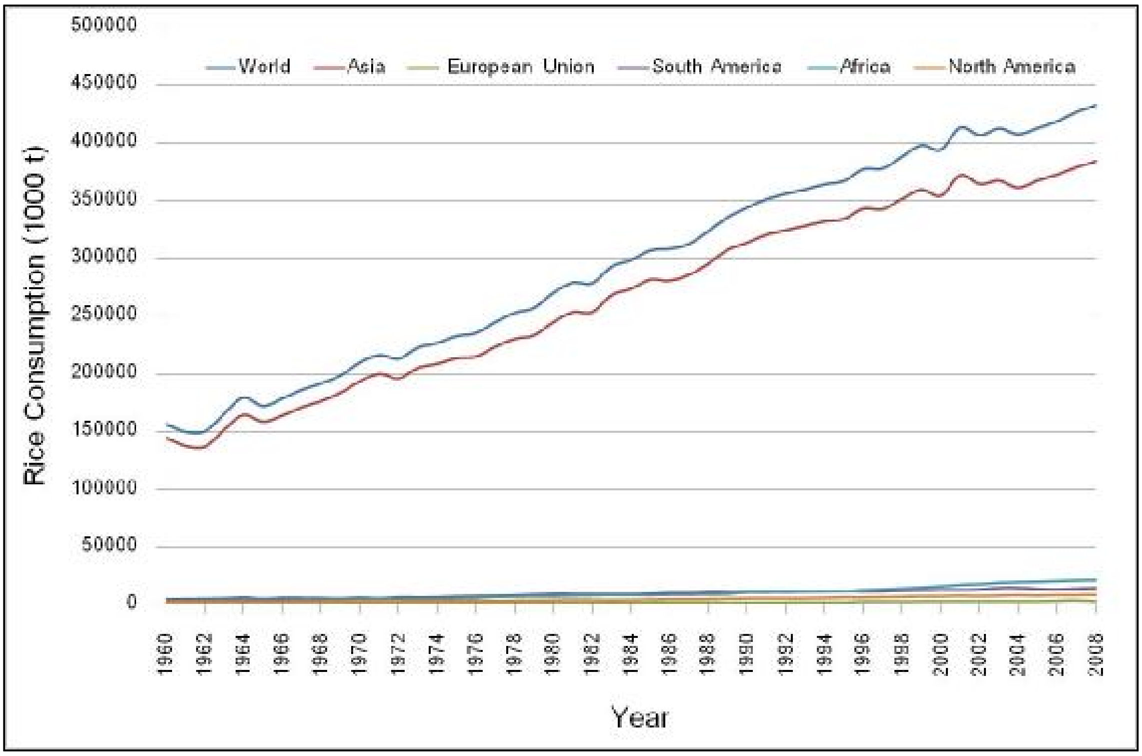


Figure 2.1 Rice consumption (000 t) in 1961-2008

Source: USDA (United States Department of Agriculture), 2009

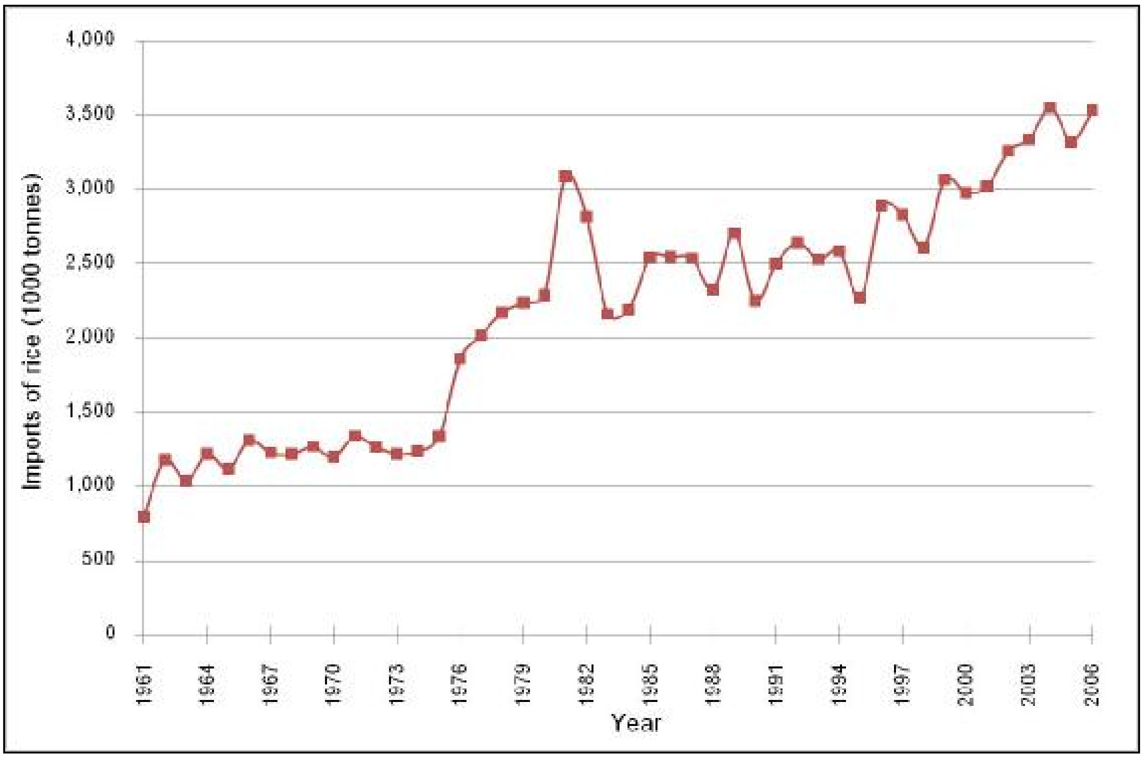


Figure 2.2 Import of rice in Europe (Source: FAOSTAT data, 2009)

2.2 Techno-Economic Analysis

Techno-economic assessment of irrigation systems and farms has long been performed. Crop budgeting, resource use analysis, productivity analysis, and farm economic assessment typically result in indicators that reflect the water supply performance (Gonzales, 2000; Edkins, 2006), agricultural production performance, and the economic efficiency (productivity) of production factors such as labour, land, water, and other inputs (Ali & Taluker, 2008; Le Grusse et al., 2009; Speelman et al., 2011).

2.3 LCA framework

While concerns regarding the environmental impacts of the agricultural sector have been raised over recent years, LCA has become a common methodology to assess these potential environmental impacts. This section presents the LCA methodology which has been applied to many kinds of agricultural products including rice production system.
Evaluation of environmental impacts is a primary function of LCA which is taking into account the entire life cycle of the product. This includes extraction of resources to the production of materials (cradle), components of the product itself, reuse, recycling and disposal still final end product (grave) (Guinee et al., 2002).

According to ISO 14040 (2006), there are four phases in LCA, as described below (Baumann and Tillman, 2004);

Goal Definition and Scoping: this phase defines and describes the product, process or activity to be studied and specifies the overarching goal underlying the research, its scope and objectives. The boundaries of the system and functional units to be assessed are also specified. It establishes the context in which the assessment is to be made and identified the environmental effects to be reviewed for the assessment.

Life Cycle Inventory (LCI): The meaning of LCI is to build a system model according to the requirement of the goal and scope definition. This phase identifies and quantifies energy, water, inputs and materials usage and environmental releases associated with each stage of production (e.g., air emissions, solid waste disposal, waste water discharges). This stage of LCA is critical because of the LCI results are needed to perform any type of quantitative impact assessment.

Life Cycle Impact Assessment (LCIA): The third stage of LCA can be performed after LCI have been quantified. Impact assessment consists of three stages: classification, characterization and valuation. Classification is the assignment of LCI inputs and outputs impacts groupings. Characterization is the process of developing a conversion model to translate LCI and supplemental data to impact descriptors. Valuation is the assignment of the relative values or weights to different impacts allowing integration across all impact categories (Curran, 1996).

Interpretation: This last phase evaluates the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

Figure 2.3 illustrates the LCA framework with the links between the four phases.

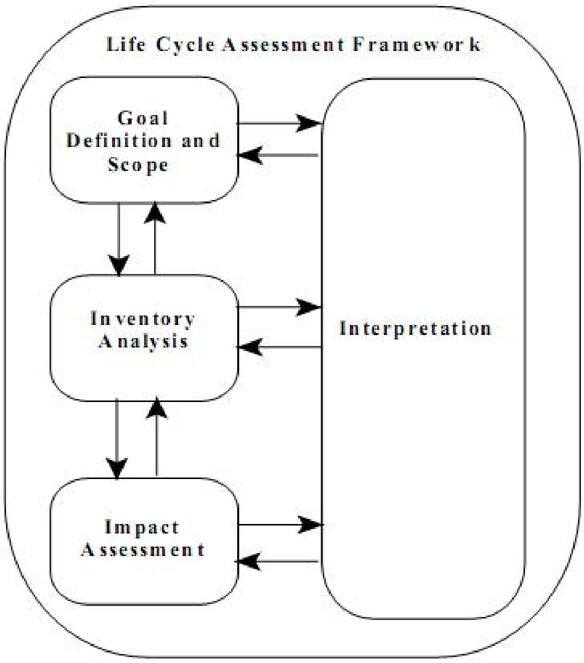


Figure 2.3 Phases of LCA *(Sources: ISO 14040, 1997)*

2.4 Life Cycle Assessment of Rice production

Since the 1960s, LCA was applied to many products; especially the industrial products and it became a standard of many countries. LCA was applied to agricultural sectors, mainly to Japanese rice production in 1999s by Breiling et al. who developed the mathematical framework to LCA by using top-down approach, related to the economic input output table to evaluate the GHG (CO_2, NO_X, SO_X) and heavy metal pollution. The model was applied to difference farm sizes, the research found that small scale causes more pollution and the average CO_2 emission is 2.33 t CO_2 emission. Breiling et al. (2005) applied the top-down life cycle approach, based on economic input output tables to estimate GHG (CH_4 & N_2O) emissions of rice related in Japan. In 2007, Harada et al. applied LCA to compare GHG between conventional puddling and no-tilling rice cultivation in Japan. The result shows that the no-tilling scenario saved on fuel consumption, totaling CO_2 output of 42 kg ha^{-1}, which was equal to the 6% reported GHG emissions from fuel consumption by operating machines during rice production in Japan. The cumulative CH_4 emissions from the no-tilling cultivation were 43% lower than conventional puddling cultivation and N_2O emissions were not significantly different between the cultivation scenarios. Roy, et al. (2007) determined the energy consumption and the environmental load (CO_2 emission) of different parboiled rice processes (vessel medium-boiler and untreated processes) in Bangladesh. The results (energy consumption and CO_2 emission) gradually decreased from the vessel to the untreated process (vessel > medium-boiler > untreated). Brodt et al. (2008) applied LCA assessed GHG emissions in California rice production and the result shows 2.82 kg CO_2-eq was released for each kg of milled rice. Hokazono et al. (2009), LCA was applied to compare among conventional, organic and sustainable (environmentally-friendly) rice production by using global warming and eutrophication potentials as indicators in Japan. Farm survey carried on a large farm (55 ha) for LC inventory over two growing seasons (2007 and 2008). The results indicated that the environmental performances depend on the functional unit (in that study, FUs namely, area, mass and monetary value). The GHG emissions (CO_2-eq) per 1 kg of brown rice are 1.52, 1.34 and 1.62 kg for conventional, sustainable and organic rice systems, respectively and eutrophication potentials in the conventional rice systems are higher than both organic and sustainable farming. It can be implied that the organic and sustainable farming have the potential to reduce environmental burdens. In 2009, Blengini & Busto applied LCA to rice production system in Italy based cradle-to-supermarket. LCA designated out the magnitude of environmental impacts per kg of delivered white milled rice. The improvement scenarios have been analyzed considering alternative rice farming and food processing methods (organic, upland and parboiling farming) and its result shows that organic and upland farmings have the potential to decrease the impact per unit of cultivated area.

In Thailand, two studies on rice LCA were published in 2008 and 2009. Yossapol and Nadsataporn (2008) applied LCA to rice production by considering 1,000 kg of unmilled grain as a functional unit, and the following environmental impact categories: Global Warming (GWP), Acidification (AP), Eutrophication (EP), Energy Consumption (EDP) and Abiotic Depletion (ADP) were assessed. In that research, the inventory analysis was defined based on the survey of 400 farms and 24 milling plats and some national and international database. Water input to the system as a resource, but the output (impact compartment) was ignored. In 2009, Kasmaprapruet et al. applied LCA to milled Rice Production in order to determine the environmental load. The results show that the global warming potential of rice production per kg was 2.93 kgCO_2-eq, followed by 3.19 gSO_2-eq of acidification and 12.90 gNO_3-eq of eutrophication and around 95% of the global warming inputs to the system are associated with the cultivation process, 2% with the harvesting process and 2% with the seeding and milling processes.

In 2012, there are 2 studies that were done by Hokazono & Hayashi and Wang et al. Hokazono & Hayashi applied LCA to investigate the variability in environmental impacts during the conversion period. In this study, time-series data obtained from a five-year on-farm trial were applied to an LCA of three rice production systems in Japan: organic, environmentally friendly, and conventional. The results showed that only the environmental impacts associated with organic farming fluctuated widely over the years across all impact categories (global warming, acidification, eutrophication, and non-renewable energy), and these fluctuations diminished over time. The environmental impacts of organic rice production were higher than those of the other two modes of rice production in four categories covered in the study on average. The cause of higher variability in the impacts of organic farming at the initial phase was associated mainly with the instability of the organic rice yield. In the same year, Wang et al. used LCA to examine the environmental impact of the rice production system in Taihu region, China with 1 ton of paddy rice as the functional unit. The analysis included raw material extraction and transportation, agrochemical production and transportation, and arable farming in the field. The result shows that the significance of environmental impacts, followed by aquatic eutrophication, water depletion, global warming, acidification, and energy depletion. The GWP of the rice production system is dominated by CH_4 and CO_2, which contributed 68 and 21% to the total GWP per ton of rice. Although N_2O emission amount was small, it contributed 11% to the total GWP of the rice production system. This is because GWP contribution of N2O is very larger than that of CO_2, hence fewer emissions of N_2O will have a greater GWP. The AP in arable farming subsystems was 21 kg SO_2 equivalent t^{-1}, accounting for 93% of the total AP of the rice production system. Nitrogen loss through ammonia volatilization constitutes a very large proportion of the N fertilizer loss from the rice production system, accounting for 60% of the total eutrophication indicator. The water depletion potential in arable farming subsystems was 379.7 t, accounting for 88% of the life cycle water depletion of the rice production system.

Table 2.1 summarizes previous studies on the LCA of rice production system.

All research on LCA of rice production, including researches done in Thailand, have largely ignored the diversity of the production systems and conditions, and the whole production chain of rice. All the researchers considered the global warming potential, some estimated eutrophication and acidification, but most researchers still missed water use, biodiversity, toxicity, energy use. Beyond water consumption per se, a question related to rice production is how does it impact on overall water availability and regional resource depletion (as a mid-point impact indicator). Across rice LCA studies, different system boundaries and allocation rules, and different functional units obviously provide different result of the potential environmental impacts, therefore prove useless for comparison. It is difficult to interpret and compare because of a lack of consistent framework and presentation in these researches. Other important differences or inconsistencies might be due to the quality of the references and the diversity of methods that used in inventory data phase, especially methods used regarding GHG emissions remain often unspecified or not local-based. Best available knowledge on direct field emissions from rice farming systems should be explored and included into more reliable and specific LCI data.

As mentioned above, the search for a better accounting of the specificities of each production context should be defended against a systematic standardization which would dramatically reduce the prediction ability of LCA studies. Four major aspects should be improved such as:

- the commonly several assumptions should be harmonized and made it clearly such as the definition of the functional unit, the allocation rules, the system boundaries and the choice of impact categories
- the consistent reporting scheme of the study
- need more of a harmonization process
- in the inventory data, the researcher or scientists should use at least the national database, should not use only the international database or literature review because some international database or literature review are not suitable for their specific areas.

2.5 Water footprint and Water use in LCA

In fact, water use impacts have been under-represented since the start of LCA methodology in the late 1960s in terms the qualitative output; acidification, eutrophication, ecotoxicity. However, there are some research considered water as a quantitative input, resources depletion and the impacts on human health and ecosystems (Mila i Canals et al., 2009; Pfister et al., 2009; Bayer et al., 2009; Ridoutt & Pfister, 2010). In consideration of water as the quantitative input to the system, the concepts and methodological of virtual water (VW) and water footprint (WF) was selected. VW is the amount of water embedded in food or other products needed for its production (Rahatwal, 2010). This concept was developed by Hoekstra and Hung (2002) which has been developed to estimate the volume of VW flows between the nations and included virtual water trade balances of nations within the context of national water needs and water availability and then this concept has been improved by Chapagain and Orr (2009). Also, WF has been developed and applied in many countries; these may be mobilized for LCA analysis. In applied of this WF concept to agricultural production, the volume of water used for crop production is composed of two components: 1) the evaporative water that is the sum of the evaporation of rainfall from crop land (green water use) and the evaporation of irrigation water from crop land (blue water use), and the non-evaporative use (grey water use) that is the polluted water resources resulting from leached fertilizers, chemicals or pesticides from agricultural land.

Formalization of LCA methodology could be useful to improve the VW (Rahatwal, 2010). There are some scientific works have been done to build a bridge between LCA and VW. The LCA in water use idea is to quantify the total water needed within a life cycle and thus, to calculate the virtual water content following a concept equivalent to LCA. In 2009, Bassest-Mens et al. investigated that VW concept to assess the differential impact at a local scale and grey water concept better addressed in the LCA framework through several impact categories (acidification, eutrophication, ecotoxicity freshwater, human toxicity, etc.).

Mila i Canals et al. (2009) assessed freshwater use impacts in LCA which developed the inventory model and characterization factors for the main impact pathways. Water enters to the system is defined as an input source and leaves the system as an output from the system (in the forms of evaporative and non evaporative uses). That research proposed the four main impact pathways related to freshwater use that may be distinguished and merit attention in LCA: 1) direct water use impact leads to changes in freshwater availability for humans leading to changes in human health; 2) Direct water use leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality (freshwater ecosystem impact, FEI); 3) Direct groundwater use causing reduced long-term (fund and stock) freshwater availability (freshwater depletion, FD); 4) Land use changes leading to changes in the water cycle (infiltration and runoff) leading to changes in freshwater availability for ecosystems leading to effects on ecosystem quality (FEI). Figure 2.4 shows the main impact pathways related to freshwater use of that study. In the same year, Pfister et al. assessed the environmental impacts of freshwater consumption in LCA which focused on endpoint impacts which shown as three areas of protection: human health, ecosystem quality and resources. Their study also included the importance of regionalizing water use estimations, and development of Water Stress Index (WSI) which reflect to local scarcity conditions. They applied their approach to cotton textiles on country level. Coltro (2010) considered the aspects of water use in two important Brazilian crops: coffee and orange and were assessed by LCA. She followed the inventory modeling for assessing freshwater impacts in LCA described by Mila i Canals et al. (2009) but considered only the impacts on ecosystem quality (from direct and water use). The results show that the average water use estimated for coffee and orange was approximately 11,400 kg of water per 1,000 kg of green coffee and 2,500 kg of water per 1,000 kg or orange. That study mentioned that the non-evaporative use for both crops is subsequently returned to the water source and it does not lead to relevant environmental impacts from a resource perspective. In the same year, Ridoutt & Poulton highlighted the importance of impact assessment in the development of life cycle-based sustainability indicators relating to consumptive water use of cereal crop in Australia and compared the results between dry-land and irrigated cropping systems. The results show that 150-fold difference in water footprint was found between the majority Statistical divisions when calculated using the method of Ridoutt & Pfister (2010), reflecting variation in the use of supplemental irrigation and local water scarcity and these differences were not evident when virtual water contents were compared.

For cereal crops grown without irrigation, input to faring such as fertilizer, pesticide, etc. made a major contribution to the water footprint.

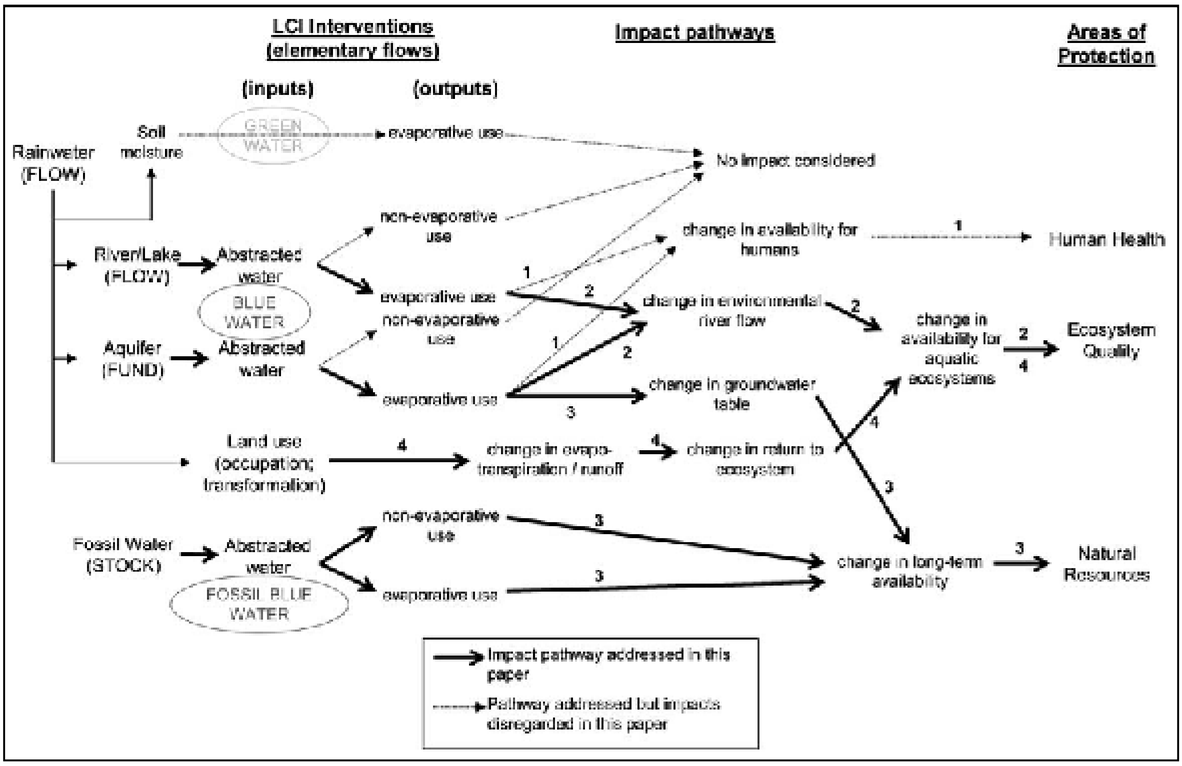


Figure 2.4 Main impact pathways related to freshwater use (Mila i Canals et al., 2009)

According to research works on the water use in LCA can be observed that the virtual water concept was applied in those studies and tend to discard the VW-related concept of grey water for the LCA. However, environmental impacts related to other impact categories can be associated with the water use, e.g.m eutrophication, acidification, ecotoxicity. For estimation of environmental potentials, Mila i Canals et al. (2009), Pfister et al. (2009), Bayer et al. (2009), Ridoutt & Pfister (2010) identified the need for more detail inventory methods (particularly the difference between blue and green water), and recommend excluding green water from impact assessment. Some studies (Mila i Canals et al., 2009; Ridoutt & Pfister, 2010) suggest that green water be handled under the category of land use in LCA. In agricultural system, water footprint research is based on retrospective analysis of crop water requirements by using CROPWAT model which developed by FAO (Wiedemann & McGahan, 2010). All the previous studies have been developed new methodological for consideration of freshwater in LCA approaches, however, the application of their to local case studies are still lacking and debated of methodology are still raging over weighting methods for WF components, and including of local key factors to agriculture consumption.

2.6 Estimation of Water Stress Indicator (WSI)

In 1980, Falkenmark proposed and indicators based on water resources (WR) per capita (equation 2.1) with defined threshold values for water stress when WRPC<1,700 m^3/capita, WRPC<1,000 m^3/capita means water scarcity and absolute water scarcity which WRPC< 500 m^3/capita.

$$\mathrm{WRPC} = \frac{\mathrm{WR}}{\mathrm{population}} \tag{2.1}$$

where; WRPC is water resources per capita
WR is water resource

With regard to assessment, many methods use the withdrawal-to-availability (WTA) ratio for calculating characterization factors for water and consumption (Berger & Finkbeiner, 2010). As shown in equation 2.2, WTA is defined as the ratio of total annual freshwater withdrawn for human uses in a specific region (WU) to the annually available renewable water supply in that region (WA). Hence, WTA serves as an index for local water scarcity.

$$\mathrm{WTA} = \frac{\Sigma\,\mathrm{WU}}{\mathrm{WA}} \tag{2.2}$$

WSI in term of WTA can be calculated by using the WaterGAP2 global model (Alcoma et al., 2003), describing the WTA ratio of more than 10,000 individual watersheds. Some studies (Coltro, 2010; Berger & Finkbiner, 2010), WTA can be called the water use per resource indicator (WUPR) which was mentioned by Raskin et al. (1997). This ratio was developed by many research to estimate water stress indicators.

WUPR was used in the study of Coltro (2010) as a characterization factor for assessment of the freshwater ecosystem impact (FEI).

Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of fresh water resources in terms of quantity; aquifer over-exploitation, dry rivers, etc. and quality; eutrophication, organic matter pollution, saline intrusion, etc. (UNEP, 2003).

Smakhtin et al. (2004) developed the equation to estimate water stress indicator (WSI) based on the basic equation. WSI can be described by the relationship between water availability, total us and environmental water requirement. As it can be seen from equation (2.3). This study estimated EWR for worldwide basin, including Thailand. EWR of basin in Thailand varies between 27-28% of mean annual runoff.

$$\mathrm{WSI}_i = \frac{\mathrm{WU}_i}{\mathrm{WR}_i - \mathrm{EWR}_i} \tag{2.3}$$

Figure 2.5 shows the map of WSI (cover 106 basins around the world) which takes into account EWR and estimated by Smakhtin et al. (2004). If WSI exceeds 1, the basin is classified as “environmentally water scarce”, 0.6<WSI<1 are arbitrarily defined here as heavily exploited or “environmentally water stressed”, basins where 0.3<WSI<0.6 as moderately exploited and environmentally “safe” basins are defined as those where WSI<0.3.

Table 2.1 Summarization of previous studies on LCA of rice production system

Studies No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
References	Breiling et al., 1999	Roy et al., 2007	Yossapol et al., 2008	Brodt et al., 2008	Hokazono et al., 2009	Blengini & Busto, 2009	Kasmaprapruet et al., 2009	Hokazono, Sh. & Hayashi, K., 2012	Wang et al., 2012
Country	Japan	Bangladesh	Thailand	California	Japan	Italy	Thailand	Japan	China
Function unit	1million yen of Rice	1 ton of milled & head rice	1,000 kg of unmilled grain	1 kg of milled rice	1 kg of rice brown, 1 ha of surface used, 1000 yens of brown rice	1 kg of delivery rice packed	1 kg of milled rice	1 kg of brown rice of organic, environmentally friendly, and conventional farming	1 ton of paddy rice
System boundary	Cradle-to-farm gate	Post-harvest to cooking	Cradle-to-mill gate	Cradle-to-mill gate	Cradle-to-farm gate	Cradle-to-supermarket	Cradle-to-mill gate	Cradle-to-farm gate	Cradle-to-farm gate
Allocation rule	Economical allocation	Mass allocation	Mass allocation	Mass allocation	unclear from paper	Economical allocation	Economical allocation	Mass and Economic allocations	not mentioned
Technical farm data	Secondary data	Secondary data	Averages from farmer and miller surveys, secondary data	Interviews with industry representative & cooperative staff, secondary data	survey interviews, national database	site records, farmers' interviews and secondary data	Average practices observed	farmers interviews and secondary data	local expert and farmer interviews, Secondary data
Direct field emission	Own model, National references	Secondary data	Thai database, Ecoinvent	Specific models, secondary data & Ecoinvent	National references	Primary & Secondary data, Ecoinvent	Asian and Thai refernces	Secondary data	Secondary data

Table 2.1 Summarization of previous studies on LCA of rice production system (Cont'd)

Studies No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Climate change	1.7 - 3.2 ton CO_2 emission	920 - 1320 kg CO_2-eq	915 – 1,013 kgCO_2-eq	1.93 - 2.82 kgCO_2-eq	7.5 - 9 MgCO_2-eq (unit area), 1.5 - 1.6 kgCO_2-eq (unit mass), 4.4 - 6 kgCO_2-eq (unit monetary value)	2.76 – 2.88 kgCO_2-eq	2.93 kgCO_2-eq	1.46 - 2.0 kgCO2-eq	1,570 kg CO_2-eq
Eutrophication	-	-	56.52 – 56.71 kg PO_4-eq	-	145 - 205 kgPO_4^{-3}-eq (unit area), 25.5 – 34.5 kgPO_4^{-3}-eq (unit mass), 0.08 - 0.14 kgPO_4^{-3}-eq (unit monetary value)	328.3 – 334.7 g O_2-eq	12.90 g NO_3^--eq	0.0076 - 0.0104 kgPO_4^{-3}-eq	13.2 kg PO_4-eq
Acidification	-	-	6.29 - 6.92 kg SO_2-eq	-	-	0.25 - 0.28 mol H^+	3.19 g SO_2-eq	0.001 - 0.0023 kg SO_2-eq	25.17 kg SO_2-eq
Ozone depletion	-	-	-	-	-	0.1 - 0.12 mg CFC11 eq	-	-	-
Energy consumption	-	1028 - 1144 kWh of electricity	-	-	-	15.72 - 17.81 MJ	-	4.6 - 6.1 MJ of Non-renewable energy	3526 MJ
Toxicity	-	-	-	-	-	-	-	-	-
Water use	-	-	-	-	-	8 - 8.2 m^3	-	-	431.1 ton
Biodiversity	-	-	-	-	-	-	-	-	-

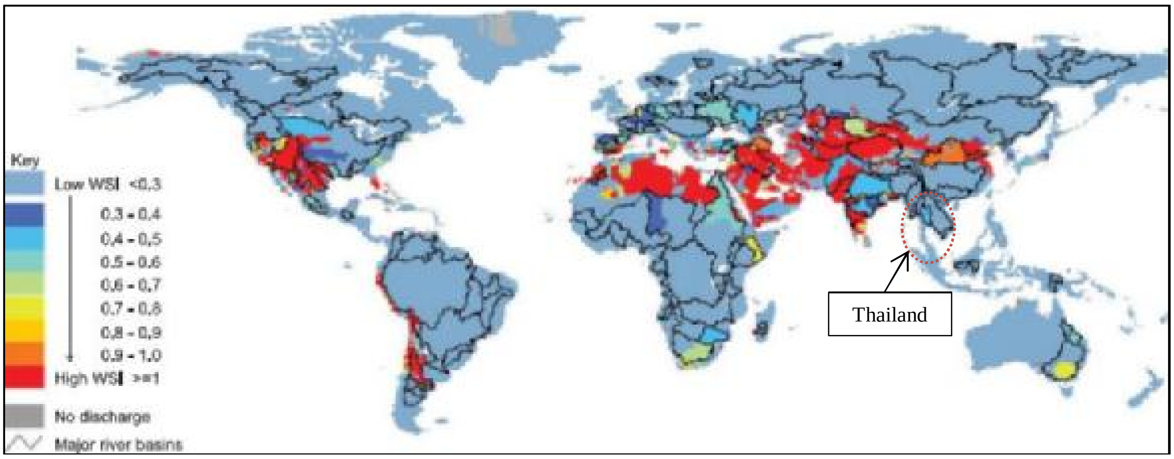


Figure 2.5 A map of water stress indicator (WSI), Smakhtin et al. (2004)

In 2009, Mila i Canals et al. suggested 3 methods to calculate WSI: 1) indicator based on water resources per capita (Falkenmark, 1980; 2) water use per resource indicator (WUPR); 3) environmental water stress (WSI=WU/(WR-EWR)). All in all the methods, Mila i Canals et al. (2009) recommended the model which takes into account the EWR (Smakhtin et al., 2004). They recommend that this model gives a more accurate indication of the water resources available for future human use after reserving the necessary resource for the ecosystem (EWR). That study provided values for the WRPC and WUPR indicators for most countries. It has been compiled using the data from FAO Aquastat database (FAO 2004) and the UNDP human development indicators (United Nations Development Programme 2006). Population, water resources and water use were the basis parameters required to construct the indicators. That study also provided values for WSI for the world's main river basins (Smakhtin et al., 2004) which show the very low WSI in Thailand basins except Chao Phraya River basin shows 0.4-0.5 by WSI.

In the same year, Pfister et al. commented on WSI which calculated by using WaterGAP2 model based on the WTA ratio (Alcoma et al., 2003) that hydrological water availability modeled in WaterGAP2 is annual average based on climate data (1961-1900). However, both monthly and annual variability of precipitation may lead to increase water stress during a specific period, if only insufficient water storage capacities are available or if much of the stored water is evaporated. To correct for increased effective water stress, they introduced a variation factor (VF) to calculate a modified WTA (WTA*, equation 2.4) which differentiates watersheds with strongly regulated flows (SRF) as defined by Nilsson et al. (2005). According to Figure 2.6, Nilsson et al. (2005) reported SRF for Thailand varies between moderately and strongly affected. This study decided to use strongly affected as the condition of the calculation.

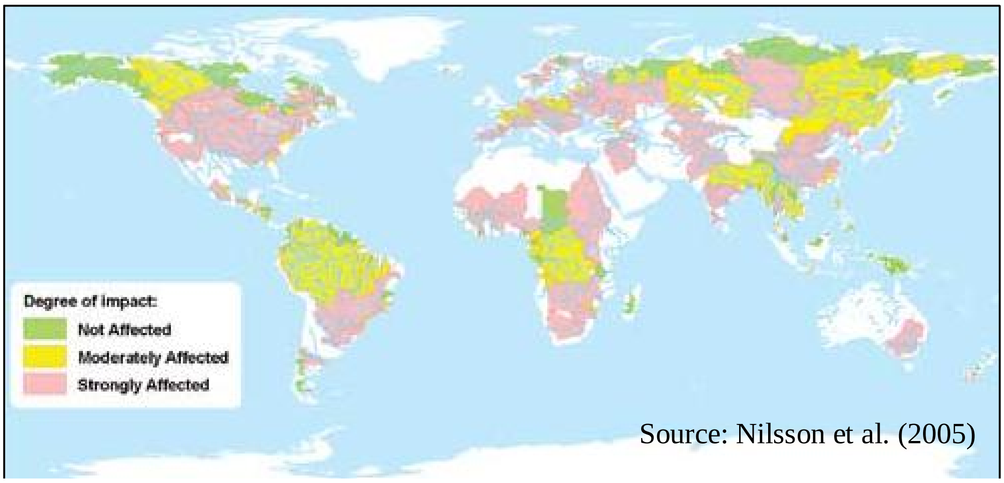
$$\mathrm{WTA}^* = \begin{cases} \sqrt{\mathrm{VF}} \times \mathrm{WTA} & \text{for SRF} \\ \mathrm{VF} \times \mathrm{WTA} & \text{for non - SRF} \end{cases} \tag{2.4}$$

where; VF is the aggregated measure of dispersion of the multiplicative standard deviation of monthly (S^*_{month}) and annual precipitation (S^*_{year}).

$$\mathrm{VF} = e^{\sqrt{\ln\left(S^*_{\mathrm{month}}\right)^2 + \ln\left(S^*_{\mathrm{year}}\right)^2}} \tag{2.5}$$

They provided the equation to calculate WSI base WTA* as shown in equation 2.6 and this equation was used to calculate WSI for basin around the world as shown in Figure 2.7 (more than 10,000 individual watersheds). WSI was used as the characterization factor to calculate the end-point impacts indicators (damage to human health, ecosystem quality and resources).

$$\mathrm{WSI} = \frac{1}{1 + e^{-6.4 \times \mathrm{WTA}^*\left(\frac{1}{0.01} - 1\right)}} \tag{2.6}$$



Source: Nilsson et al. (2005)

Figure 2.6 Impact classification based on river channel fragmentation and water flow regulation by dams on 292 of the world's large river systems.

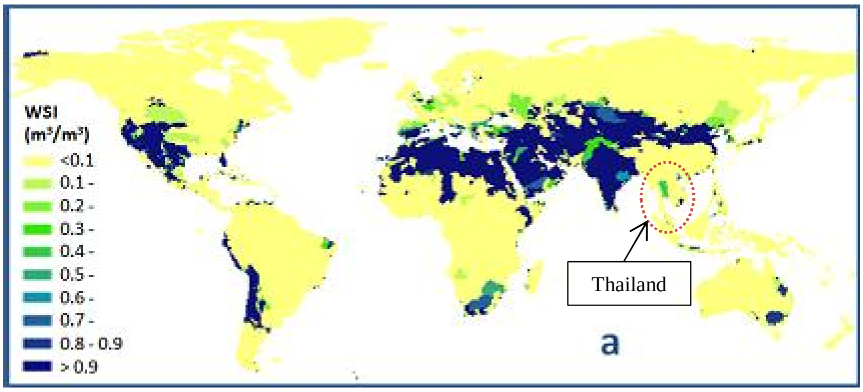


Figure 2.7 Water stress index by Pfister et al. (2009)

Ridoutt & Poulton (2010) applied WSI of Pfister et al. (2009) to calculate the midpoint impact indicators of wheat, barley and oats production in New South Wales, Australia. Pfister et al. (2009) presents WSI less than 0.1 in the Thailand basin except Chao Phraya river basin, which shows 0.3-0.4 by WSI. Rahatwal (2010) used WSI value of Thailand

(WSI = 0.5) which calculated by Pfister et al. (2009) to calculate the stress weighted water footprint in Klong Yai Basin, Thailand both dry season and wet season.

Babel & Wahid (2009) developed an approach to estimate WSI by aggregating nine water stress parameters: 1) water scarcity parameter (Falkenmark, 1980), 2) water variation parameter, 3) water exploitation parameter, 4) safe drinking water inaccessibility parameter, 5) water pollution parameter, 6) ecosystem deterioration parameter, 7) water use inefficient parameter, 8) improved sanitation inaccessibility, 9) conflict management capacity. This method requires the weighting factor between each parameter which based on expert consultation. The weight can vary between 0-1 and total of the weights should equal to 1. They also prepared the criteria for interpretation of WSI; 0.0-0.2 is low WSI, 0.2-0.4 is moderate, 0.4-0.7 is high and 0.7-1.0 is severe. They applied this approach to selected basin in South, Southeast and Northeast Asia. In 2010, Rahatwal also applied this approach to Klong Yai Basin, Thailand, but considered only four water stress parameters which are water scarcity parameter, water variation parameter, water exploitation parameter and water pollution parameter. The weight of each parameter was calculated by using AHP (Analytical Hierarchy Process) which developed by Thomas Saaty, (1990). He found that the average WSI Klong Yai Basin in is equal to 0.54 and it closes to 0.5 of WSI which estimated by Pfister et al. (2009).

IWMI (2008) shows that in Thailand there is a little or no water scarcity in the area as shown in Figure 2.8. Regarding to Figure 2.9, Vorosmarty, et al. (2010) reported that there is a very high incident, threat to human water security (almost 1.0) in Thailand.

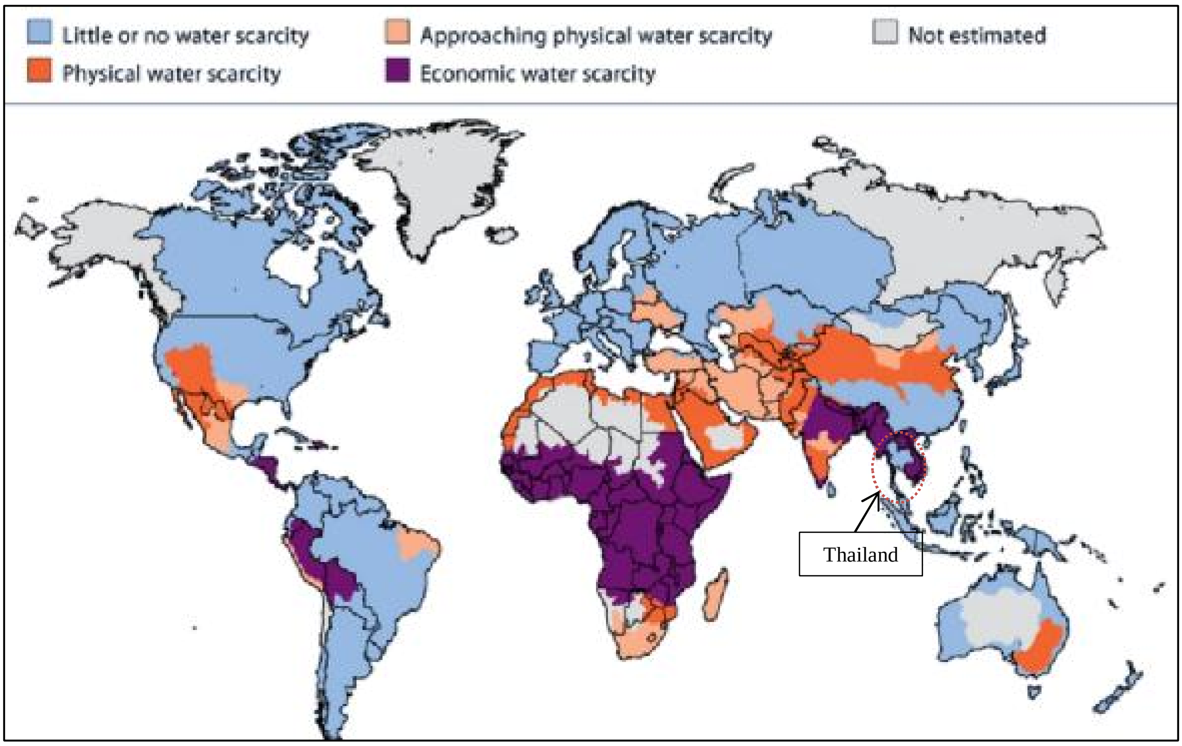


Figure 2.8 Areas of physical and economical water scarcity on a basin level in 2007 (IWMI 2008).

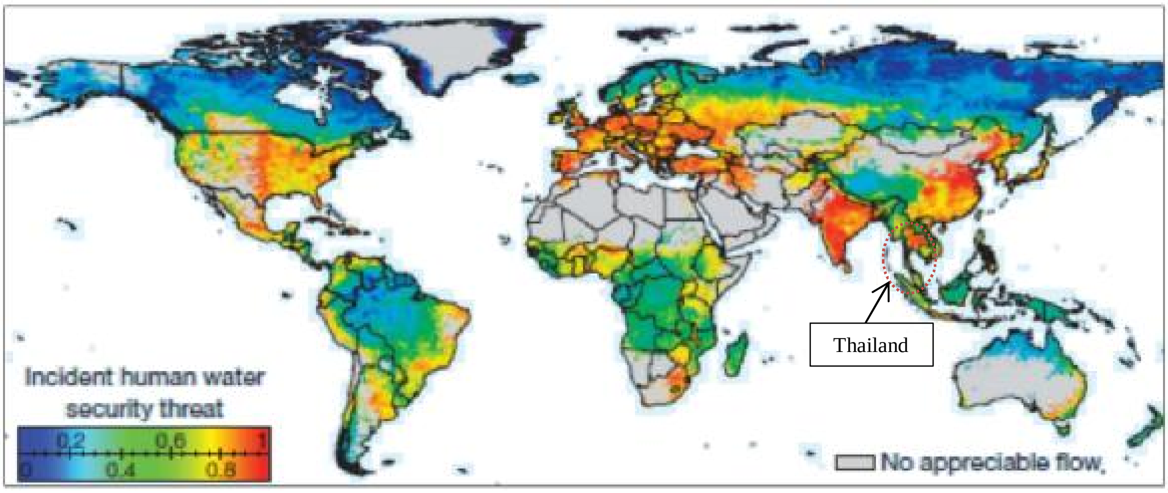


Figure 2.9 Global geography of incident threat to human water security (Vorosmarty, et al. 2010).

According to Pfister et al. (2009), the characterization factor for the midpoint indicator “freshwater depletion” is $F_{depletion}$ which can be calculated as below.

$$F_{deplrtion} = \begin{cases} \dfrac{WTA - 1}{WTA} & \text{for } WTA > 1 \\ 0 & \text{for } WTA \leq 1 \end{cases} \qquad \text{(equation 2.7)}$$

Table 2.2 presents the summarization of methods to estimate water stress indicators.

In the same year (2009), Pfister et al. suggested using WSI as the characterization factor for determining the impact of water use (midpoint category) or so called “water deprivation potential (WDP)” in LCIA. The WDP can be calculated from the multiplication of blue water with the WSI as shown below which is measured in m^3 water equivalents (m^3 eq)

Water Deprivation Potential = Blue water x WSI

Gheewala et al. (2014) estimated WSI at whole river basin level in Thailand. They used Pfister et al. (2010) as the guline for calculation of WSI. The resulting of WSI are also very different between basins.

2.7 Eco-Efficiency analyses

Eco-efficiency (EE) is a workable approach to sustainability at the farm level consists in evaluating whether producers are making efficient use of resources and minimizing environmental impacts while achieving their economic objectives. This concept emerged in the 1990s to allow for a practical approach to sustainability (Schaltegger, 1996; Tyteca, 1996; OECD, 1998; Schaltegger & Synnestvedt, 2002; Bleischwitz, 2003). EE expresses how efficient an economic activity is with regard to its impact upon nature. EE is represented by the ratio “Product or service value / Environmental influence” (OECD, 1998). The concept of eco-efficiency has proven to be a practical tool for enhancing both economic and environmental benefits. To date, it has had a focus on resource use vs. broad economic outputs (e.g., energy use vs. GDP or turnover), and eco-efficiency has yet to fully develop at the micro level and in the agricultural sector and to consider the diversity of environmental impacts.

Table 2.2 Summarization of method to estimate water stress indicators (WSI)

No.	Researchers	Year	Type of study	Method of Approach to Estimate WSI	Detail
1	Raskin et al.	1997	Development	withdrawal-to-availability (WTA) ratio or water use per resource indicator (WUPR)	Gave the meaning of water stress based on water use and water availability
2	Falkenmark	1998	Development	water resources (WR) per capita	Intended to apply to human direct (domestic) use (drinking & sanitary), but did not considered water use by agricultural sector
3	Alcoma et al.	2003	Development	withdrawal-to-availability (WTA) ratio or water use per resource indicator (WUPR)	Developed the WaterGAP2 global model to estimate WSI in several basins
4	Smakhtin et al.	2004	Development	WSI = WU/(WR-EWR)	Combination environmental water requirement with the water resources available and their use
5	Mila i Canals et al.	2009	Application	WSI = WU/(WR-EWR)	Suggested 3 method (No.1, 2, 4) but recommend the method No.3
6	Pfister et al.	2009	Development	$\mathrm{WTA}^* = \begin{cases} \sqrt{\mathrm{VF}} \times \mathrm{WTA} & \text{for SRF} \\ \mathrm{VF} \times \mathrm{WTA} & \text{for SRF} \end{cases}$ $\mathrm{VF} = e^{\sqrt{\ln\left(S^*_{\mathrm{month}}\right)^2 + \ln\left(S^*_{\mathrm{year}}\right)^2}}$ $\mathrm{WSI} = \frac{1}{1+e^{-6.4 \times \mathrm{WTA}^* \left(\frac{1}{0.01} - 1\right)}}$	Modified the WAT which took into account the variation of precipitation and gave the WSI equation
7	Babel & Wahid	2009	Development	WSI can be obtained by aggregating nine water stress parameters.	Developed the approach to estimate WSI based on nine parameters. Weighting factors between each parameter are needed and to set up these factor, experts of consultation is needed
8	Rahatwa	2009	Application	Babel & Wahid and Pfister et al.'s method	Compared stress virtual water between calculation of WSI by Babel & Wahid and Pfister et al.'s method
9	Coltro	2010	Application	withdrawal-to-availability (WTA) ratio or water use per resource indicator (WUPR)	Took the WUPR value of Brazil from Alcoma et al.'s study
10	Ridoutt & Poulton	2010	Application	Pfister et al.'s method	Applied Pfister et al.'s method to cereals production in New South Wales
11	Berger & Finkbiner	2010	Application	WUPR and WSI = WU/(WR-EWR)	Summarize & introduced the methods to estimate WSI

To calculate eco-efficiency, joint of LCA and techno-economic analyses can be applied, which is mentioned in this chapter (section 2.10) and chapter of methodology.

2.8 Data Envelopment Analysis (DEA) technique advantages

There are two types of test data and consequently different types of analysis. At the Table 2.3 shows, parametric data have an underlying normal distribution which allows for more conclusions to be drawn as the shape can be mathematically described. Anything else is non-parametric.

Table 2.3 Comparison between Parametric and Nonparametric analysis

Detail	**Parametric**	**Non-parametric**
Assumed distribution	Normal	Any
Assumed variance	Homogeneous	Any
Typical data	Ratio or Interval	Ordinal or Nominal
Data set relationships	Independent	Any
Usual central measure	Mean	Median
Benefits	Can draw more conclusions	Simplicity; Less affected by outliers

DEA is an established and well known methodology for nonparametric estimating the relative efficiency of a number of homogeneous units, commonly designated as Decision Making Units (DMU) (Cooper et al., 2000, 2004; Zhu, 2002). Using this approach, there are many advantages or usefulness which many researchers mentioned in their studies. Piot-Lepetit et al. (1997) said that DEA technical inefficiency is important basis for opportunities for adjustment of inputs without loss in outputs. Dyckhoff & Allen (2001) mentioned that is a well-established methodology for the assessment of performance of homogeneous set Decision making units (DMUs) and it does not require explicit weights. Reig-Martínez & Picazo-Tadeo (2004) recommended that DEA is allowed the technological frontier to be constructed without imposing a parametric functional form on technology or on deviations from it (inefficiencies) and DEA approach permits the construction of a surface over the data which allows to comparison of one production method (or best producer) with the others, in term of a performance index. In 2009, Lazano et al., mentioned that DEA captures the dependence between the inputs and the outputs, inferring from the observed data the maximum amounts of outputs that can be obtained from different combinations of the inputs. It does not make any assumption about the functional form of the dependence between outputs and inputs and does not need or use any specific knowledge about the process. DEA makes only some basic assumptions (like convexity, scalability and free disposability) and with those few assumptions and the observed data it is able to extrapolate a production possibility set that contains the feasible operation points. Reig-Martínez & Picazo-Tadeo (2004) and Lazano et al. (2009) mentioned that DEA readily incorporate multiple input and outputs.

There are differences between linear programming and DEA; linear programming models are used to find an optimal solution for optimization problems. Linear programming models are composed of decision variables and numerical values that are arranged into a linear objective function and a set of linear constraints. The variables are not allowed to be negative. Data envelopment analysis (DEA) does not directly aim at optimization. It is a linear-programming-based technique for measuring the relative performance of organizational units where the presence of multiple inputs and outputs makes comparisons difficult. Some of the units will be deemed to be efficient and may be considered as representing the best practice available. If a suitable set of measures can be defined, DEA provides an efficiency measure not relying on the application of a common weighting of inputs and outputs. Additionally, the method identifies peer units and target values for inefficient units. The main benefits of DEA are two-fold: the performance is based on taking all the available data into account, so it gives a good reflection of overall performance, and because it is a peer based comparison the targets set for improvement are realistic.

2.9 Using DEA techniques in agricultural sector

The use of DEA techniques has been habitual in tackling the efficiency issue in agriculture (Martinez & Picazo-Tadeo, 2004). In 1996, Llewelyn & Williams applied nonparametric analysis of technical efficiency for irrigated farms in the Madiun regency in the west-central part of East Java, Indonesia which is conducted using linear programming techniques. The results show that inefficient farms use excessive levels of inputs, particularly nitrogen fertilizer and it is perhaps due to the lingering effects of past input subsidization policies, particularly of fertilizers, in Indonesia, or to risk-reducing behavior. The results also imply that to encourage diversification of cropping practices in Java may lead to greater technical inefficiencies in production. Piot-Lepetit et al. (1997) considered the usefulness of DEA for identification of opportunities for reduction in persistent technical inefficiency in the use of agricultural inputs which are associated with environmental impacts. They applied this approach to French cereal production. They concluded the technical inefficiency definitely provides an important basis for opportunities for adjustment of inputs without loss in outputs. They also concluded that farm use of fertilizers and pesticides presents and important opportunity for reduction of environmental impacts. Wadud & White (2000) compare estimates of technical efficiency obtained from the stochastic frontier approach and the DEA approach using farm-level survey data for rice farmers in Bangladesh. Technical inefficiency effects are modeled as a function of farm-specific socioeconomic factors, environmental factors and irrigation infrastructure. They concluded that from both the approaches indicate that efficiency is significantly influenced by the factors measuring environmental degradation and irrigation infrastructure. In the same year, Shaficq & Rehman (2000) identified sources of resource use inefficiency for cotton production in Pakistan's Punjab by using the DEA approach. DEA is applied to study the relative technical and allocative efficiencies of individual farms which use similar inputs, produce the same product and operate under comparable circumstances. The result shows that the use of DEA technique provides a clear identification of both the extent and the sources of technical and allocative inefficiencies in cotton production. In 2003, Iráizoz et al. estimated technical efficiency in the horticultural production sector in Navarra (Spain). Tomato and asparagus production are analyzed separately and both a non-parametric and a parametric approach to a frontier production function are used and the differences in the results are discussed. The results indicated that both tomato and asparagus production are relatively inefficient, with potential in both cases for reducing input and increasing output. They concluded that these results hold regardless of whether the frontier was parametric or non-parametric. The estimated measures of technical efficiency were positively related to the partial productivity indices and negatively related with the cultivation costs per hectare. No conclusive results were obtained from the relation between size and efficiency. Reig-Martínez & Picazo-Tadeo (2004) suggested DEA as an appropriate analytical tool to explore the possibilities of short-term viability of individual farms, after eliminating current inefficient practices and they applied this approach to Spanish citrus farms. They performed three different exercises using detailed quantity and price information on output and inputs for 33 citrus farms in the region of Valencia (Spain). The results obtained from short-term net income maximization suggest that many farms that are not viable when only observed data are considered, could become viable by eliminating productive inefficiencies.

2.10 Combined application of LCA and DEA

In 2009, Lazano et al. proposed a joint application of LCA and DEA and the step of link are described as follows.

- First step is to carry out individual LCIA for each of the DMUs to obtain the estimation of the corresponding environmental impacts for a number of impact categories.
- Secondary step is an operational efficiency analysis, which is to benchmark the production processes of the different DMUs using as inputs their LCI data and as output their corresponding functional unit. Note that the proposed DEA model only has inputs and outputs. The next step in DEA is the determination of a production possibility set.

They applied this approach to 62 mussels cultivation sites (rafts). For each site (raft) both its inputs consumption and mussels production are known and a separate LCA of each site has been performed and its corresponding environmental impacts have been estimated and then DEA is applied to estimate efficiency of each DMU. The results show that 24 of the 62 DMUs are efficient with an average efficiency of 59.69% and this allowed important input reduction (larger than 50% in some cases) which should translate into significant reductions in environmental impacts, up to 20%.

Vázquez-Rowe et al. (2010) combined LCA and DEA in order to increase the ability of both tools when applied to fisheries. Specifically, the joint inclusion of economic aspects and the consideration of currently underrepresented environmental impact categories are tackled. They presented five-steps to combine LCA and DEA that operational benchmarking and eco-efficiency verification are included together with the assessment of the environmental performance of fishing vessels. Figure 2.10 presents the proposed LCA+DEA methodology for fisheries comprises five main steps:

1.) LCI for each of the DMUs: input and output data for the assessed system are collected.
2.) LCIA for every DMUs from the LCI development in the first step.
3.) DEA from the LCIs of the first step: Determination of the operational efficiency of each DMU and calculation of the target DMUs. The DEA targets represent virtual DMU which consume less input and/or produce more output.
4.) Environmental characterization of the target DMU. In this fourth stage, the potential environmental impacts are determined for the virtual DMUs by performing an LCIA with the new LCI data arising from the previous step.
5.) Comparison of the potential environmental impacts for the virtual DMU versus those for the current DMU. This step shows how environmental impacts depend on the efficiency with which operations are carried out. Links between operational efficiency and environmental impacts are then established and the environmental consequences of operational inefficiencies can be estimated.

The results show that the use of the five-step LCA+DEA method for fisheries demonstrated the dependence of environmental impacts on the operational performance of the vessels. Operational inefficiencies were detected and target performance improvement values were consequently defined for the inefficient vessels. The combined method favored quantification of potential eco-efficiency gains. Optional features of DEA models allowed the inclusion of controversial impact issues such as by-catch discarding.

As mentioned above, conventional DEA analyzes how known quantities of inputs contribute to one or combined quantities of outputs in a production process; terms differ according to sources as such analysis may refer to technical efficiency (De Koeijer et al., 2002; Kiatpathomchai et al., 2009), productive efficiency (Callens and Tyteca, 1999; Reig-Martinez and Picazo-Tadeo, 2004) or operational efficiency (Lozano et al., 2009). The conventional DEA analysis also allows assessing the performance of individual DMUs taking only into account observed quantities of marketable inputs and outputs. As the field of DEA applications has progressively grown, a distinctive research stream has focused on employing this technique to address the environmental consequences of production processes. One possible approach consists of handling not only conventional outputs and inputs in models, but also bad or environmentally undesirable outputs, i.e., wastes and polluting effluents obtained as by-products of commercial outputs, and inputs (Tyteca, 1996; Allen, 1999; Scheel, 2001; Zhou et al., 2008). Another approach, suggested by De Koeijer et al. (2002), calculates environmental efficiency scores with an input-oriented DEA model using observed environmental impacts instead of conventional inputs. Similarly, Zhang et al. (2008) analyses eco-efficiency using linear programming, where undesirable outputs were treated as inputs. This latter approach has been retained for analyzing the environmental efficiency of paddy rice cropping systems.

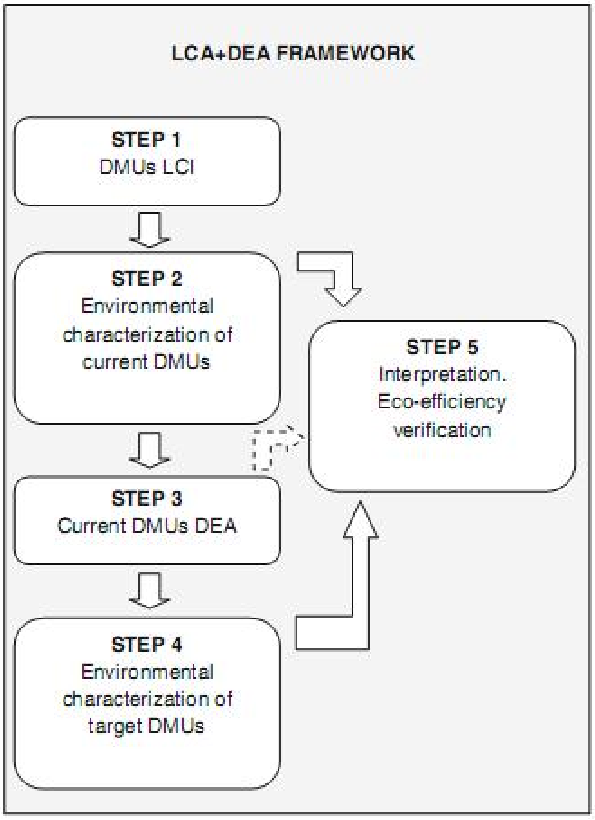


Figure 2.10 Schematic of the LCA+DEA methodology (Vázquez-Rowe & Iribarren, 2010)

CHAPTER 3

A PRESENTATION OF CASE STUDY AREAS

The criteria for selecting research case study areas have been set as follows:

- the selected sites should grow Hom Mali rice, i.e. should be located in the main production areas: North and Northeast; the sites should represent the climatic contract between the two areas, especially in terms of precipitation, water availability, runoff,
- the sites should have both irrigated and rainfed cropping systems, and also different planting methods (transplanting, direct seedling) to reflect the actual diversity,
- the sites should have enough secondary data, especially meteorological data and rice production information.

It was then decided to select one river basin for each region, which basins being sufficiently different from each other, respectively representative of their whole region, and homogenous enough yet showing the diversity of systems (rainfed, irrigated in wet and dry season). Final selection has been based upon the following sources:

- Interviews with exporters of jasmine fragrant (Hom Mali) rice in Thailand;
- Interviews with officials and experts on Hom Mali rice of Ministry of Agriculture and Cooperatives (MOAC) of Thailand;
- Interviews with RID's officials;
- Review and analysis of survey reports of the major rice crop year 2005-2009, issued by the Office of Agriculture and Cooperatives, MOAC of Thailand;
- Review and analysis of a report on "The technology of producing good varieties of rice" developed by the Rice Research Institute, Department of Agriculture.
- Review and analysis of secondary data on average runoff per unit area in the selected regions.

We ultimately chose Lam Sieo Yai basin in Northeastern Thailand, and Nam Mae Lao basin in the North of Thailand, for they matched well our selection criteria and were approved as study area by experts.

3.1 First site : Lam Sieo Yai basin (Northeast of Thailand)

3.1.1 Topography

Lam Sieo Yai basin is a plateau with an average elevation of approximately 100 to 200 m above sea level. Its area has size around 2,875 km^2. It covers 3 provinces; Mahasarakam, Roi Et, Sisaket and 7 districts. Historically, this area had suffered desert-like condition during dry season and flooding during rainy season. Soil also had salinity problem. However, the area has been treated and nowadays the plateau becomes famous rice producing area of Thailand.

Table 3.1 Information of Irrigation project in each sub-basin in North and Northeast of Thailand

Region	Information of Irrigation system					Information of Sub-Basin								
	Name of Irrigation Project	Irrigated area (rai)	Province	District	Main Irrigation	Sub-Basin Name	Average runoff (MCM / km^2)	Province	District	Total Station		Land use	Crop	
										Rainfall	Meteorological		Wet season	Dry season
North	Mae Tang Irrigation Project	148,402	Chiangmai	Mae Tang, Mae Rim, Muang, Hang Dong, San Pa Tong.	Mae Tang wier	Second Part of Mae Nam Ping	0.19	Chiangmai	Mae Tang, Mae Rim, Muang, Hang Dong and San Pa Tong, Saraphi	5	1	A = 38% F = 40% M = 5% U = 16% W = 1%	Kao Dok Mali 105 Orchard RD6	Second Rice orchard Cereal crop Vegetable
	Mae Faek - Mae Ngat Irrigation Project	270,000	Chiangmai	Sansai, Mae Rim, Muang, Saraphi, Mae Tang	Mae Ngat Dam Sintukitprecha weir	Second Part of Mae Nam Ping	0.19	Chiangmai	Mae Tang, Mae Rim, Muang, Hang Dong and San Pa Tong, Saraphi	5	1	A = 38% F = 40% M = 5% U = 16% W = 1%	Kao Dok Mali 105 RD6 orchard Vegetable	Second Rice, Field crop; Soybean, potato, Tobacco Vegetable orchard
	Mae Kuang Irrigation Project	175,000	Chiangmai Lamphun	Sansai, Doi Saket, San Kamphang Ban Thi, Muang	Mae Kuang Dam	Nam Mae Kuang	0.3	Chiangmai Lampang	Sansai, Doi Saket, San Kamphang, Saraphi, Mae on Ban Thi, Muang, Mae Tha	5	1	A = 31% F = 58% M = 2% U = 8% W = 1%	Kao Dok Mali 105 RD6 orchard Vegetable	Second Rice, Field crop; Soybean, potato, Tobacco Vegetable orchard
	Mae Lao Project	148300	Chiangrai Pharayao	Muang, Mae Lao, Phan Mae Jai (Some areas)	Mae Lao wier Mae Sulai	Nam Mae Lao	0.61	Chiangrai	Mae Sulai, Meung, Mae lao, Phan, Wiang Papao, Wiang Chai	4	1	A = 29% F = 67% M = 0.5% U = 3% W = 0.5%	Kao Dok Mali 105 RD6 orchard Vegetable	Second Rice, Field crop; Soybean, potato, Tobacco Vegetable orchard
	KewLom-KewKhoMar Irrigation Project	57,200	Lampang	Chae Hom, Muang	KewLom Dam KewKhoMar Dam	Middle part of Mae Nam Wong	0.15	Lampang	Chae Hom, Muang	1	1	A = 24% F = 60% M = 9% U = 6% W = 1%	Kao Dok Mali 105 RD6 Orchard	Second Rice, Field crop, orchard Vegetable
N/E	Sieo Yai basin	10,877	Mahasarakam Roi Et Sisaket	Wapi Phatum Pathumrat, Kaset Wisai, Suwan Phum, Phon Sai, Phanom Phai Rasi Salai	Nong Bor, Nong Tu, Nong Beng Reservoir	Lam Sieo Yai	0.16	Mahasarakam Roi Et Sisaket	Wapi Phatum Pathumrat, Kaset Wisai, Suwan Phum, Phon Sai, Phanom Phai Rasi Salai	4	1	A = 83% F = 5% M = 3% U = 5% W = 4%	Kao Dok Mali 105 RD6 orchard	Kao Dok Mali 105 Second rice orchard
	Lower Part of Mun	143,260	Sisaket Roi Et Surin	Rasi Salai, Bung Bun Phon Sai Ratanaburi	Rasi Salai weir	Second part of Lam Nam Mun	0.3	Sisaket Surin Roi Et Mahasarakam Burirum Ratchasrima	2 distric 9 districts 2 districts 1 districts 7 districts 3 districts	6	1	A = 85% F = 5% M = 4% U = 4% W = 2	Kao Dok Mali 105 RD6 orchard	Kao Dok Mali 105 Second rice orchard

Source: RID, Royal Irrigation Depart of Thailand (2009), LDD, Land Development Department, 2002

Where; A, F, M, U and W are stand for the area of agricultural, forest, miscellaneous, urban and water body, respectively

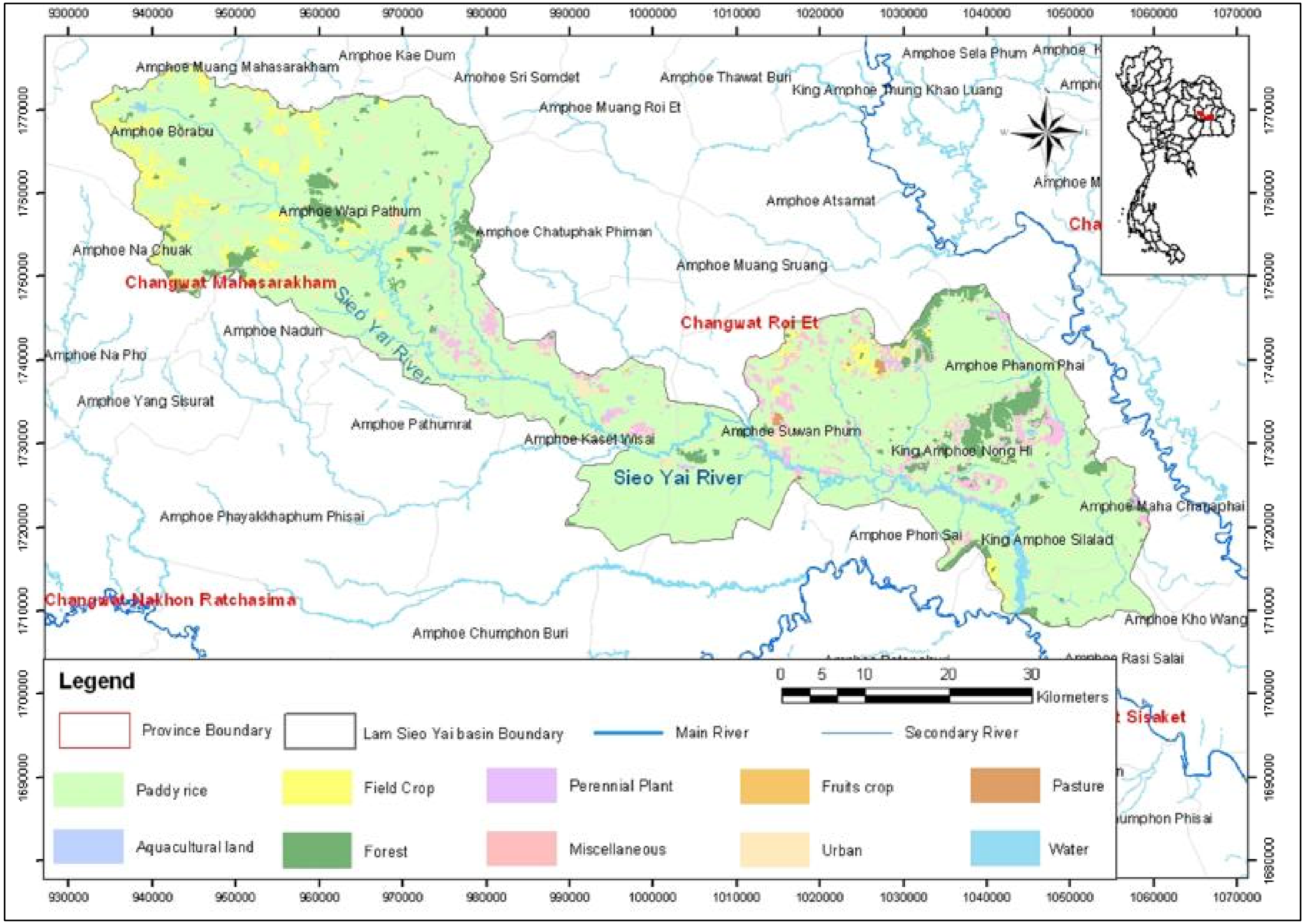


Figure 3.1 Site selection and its land use in Lam Sieo Yai basin (Northeast of Thailand)

3.1.2 River and Runoff

Sieo Yai River is the main river of Lam Sieo Yai basin (Figure 3.1) which flow along the basin. This river joins with Mun in Rattana Buri districts, Surin province and then flow to Mekong River.

3.1.3 Climate

Normally, the climate of this area is a tropical savanna climate. Its average annual temperature is 18°C. There are three seasons: the rainy season from the middle of May to the end of October, cold season from November to the middle of February, and the hot season from February to the middle of May, The area is dominated by tropical cyclones which originate over the south China Sea, resulting in high levels of rainfall which average 1400 mm per year. However, the distribution of rainfall is uneven. Eighty percent of the total rainfall occurs in the months of August and September and is accompanied by excess runoff into Mun Rivers and finally into the Mekong. This is due to the lower water holding capacity of the soils in this area.

3.1.4 Land use

The land use pattern of this area is characterized to 5 categories which are agricultural area, forest, urban, miscellaneous and water bodies (Figure 3.1). In agricultural areas, there are 6 types which are paddy field, field crop, perennial plant, fruits crop, pasture and aquacultures land. From land use map of Lam Sieo Yai basin, Northeast of Thailand (Figure 3.1), it was found that 83% of the total area are the agricultural area and around 96% of the agricultural area is paddy field and another 4% are other type of agricultural sectors.

3.1.5 Cropping systems and water management

Around 75% of paddy field is under irrigation system which under control of Sieo Yai basin irrigation project, therefore this irrigated area can grow rice (especially, Kao Dok Mali 105) in both wet & dry seasons. On the other hand, 25% of paddy field are under rainfed which grow rice one time per year, but some parts of this area which near the Sieo Yai river, farmers can grow second rice or fruit crop. Table 3.1 shows that the average runoff per unit area is 0.16 MCM/km^2/yr.

3.2 Second site: Nam Mae Lao basin (North of Thailand)

3.2.1 Topography

About 67% of the area consists of mountains covered with forests and 33% of the total area is flat. Its area has size around 2,798 km^2. It covers Chiang Rai province and 6 districts which are Phan, Muang, Mae Lao, Wiang Chai, Mae Salai and Wiang Papap. An average elevation in the area of approximately about 300 meters above mean sea level. Figure 3.2 shows the boundary of the Nam Mae Lao basin.

3.2.2 River and Runoff

The main river of this study is Nam Mae Lao as shown in Figure 3.2. Nam Mae Lao joins with Kok River and then flow through the Mae Khong river. Table 3.1 shows that the average runoff per unit area is 0.61 MCM/km^2/yr

3.2.3 Climate

There are three seasons in a year; the rainy season from June to October, the hot season from March to May, and the cold season from November to February. Generally, Chiang

Rai is cool and pleasant for the most parts of the year. The coolest months are December and January. The temperature throughout the year varies between 14-30°C, while the yearly average temperature is 26° C

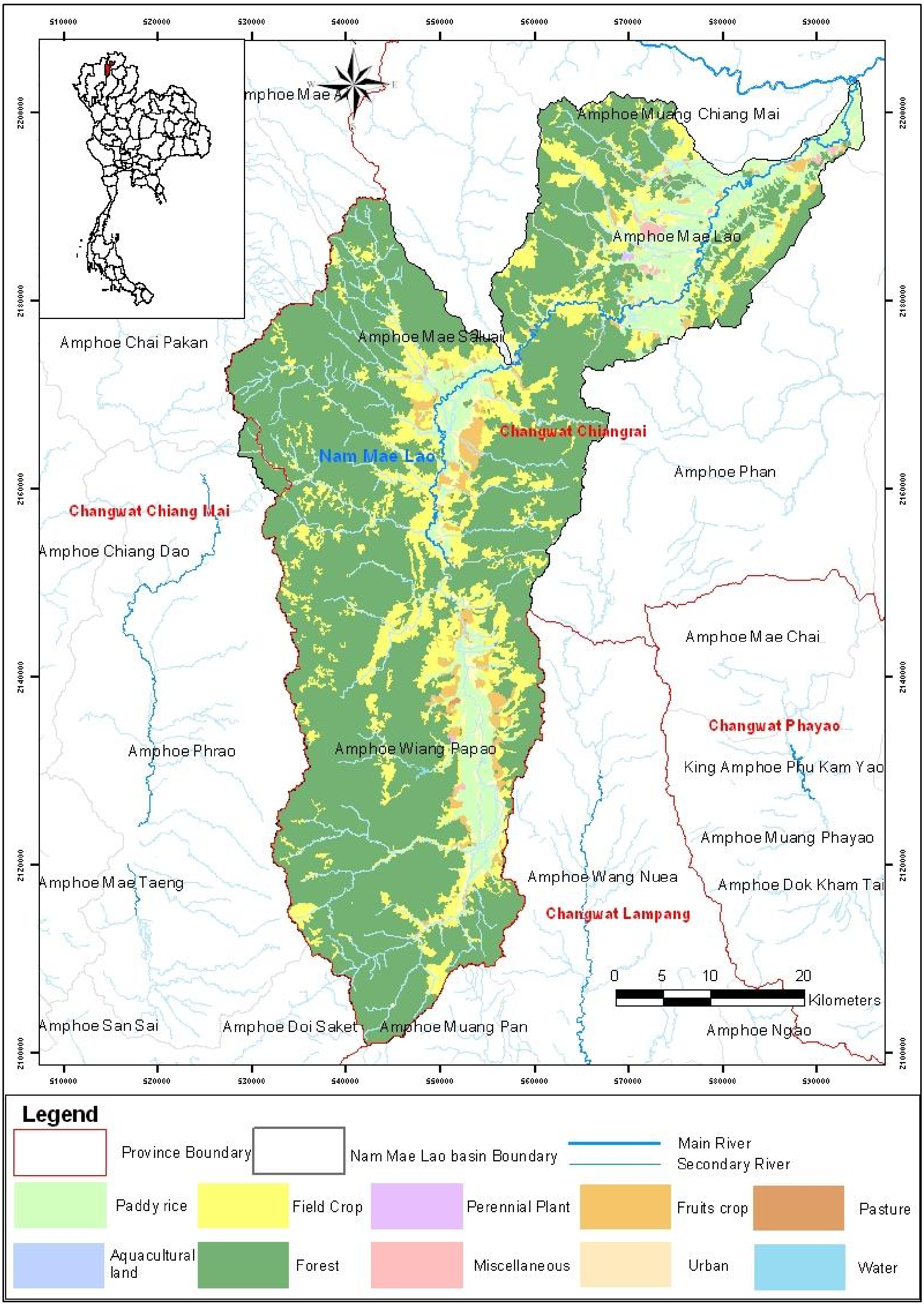


Figure 3.2 Site selection and its land use in Nam Mae Lao basin (North of Thailand)

3.2.4 Land use

The land use pattern of this area is characterized to 5 categories which are agricultural area, forest, urban, miscellaneous and water bodies (Figure 3.2). In agricultural areas, there are 5 types which are paddy field, field crop, fruits crop, horticulture and aquacultural land. From land use map of Nam Mae Lao basin (North of Thailand) (Figure 3.2), it can be noted that maximum of the land use type is rice cultivation area. The main district (Muang district) is also located in this area, captures a large number of tourists and industrial sites and less of paddy field or other agriculture activities.

3.2.5 Cropping systems and water management

Around 70% of paddy field is under irrigation system (Mae Lao Irrigation Project), therefore this irrigated area can grow rice both wet & dry seasons. On the other hand, 30% of paddy field are under rainfad which grow rice one time per year but some parts of this area which near the river, farmers can grow second rice or fruit crop.

3.3 Conclusions: why are the selected basins of interest for the study?

The Nam Mae Lao and Lam Sieo Yai basins have been selected because they both represent well the diversity of rice systems that prevail in the North and Northeast of Thailand, respectively. In both regions, three seasonal cropping systems do exist in various proportions, i.e. rainfed (uncontrolled irrigation, also known as controlled drainage) during the wet season (Rw), irrigated during the wet season (Iw), and irrigated during the dry season (Id). Our selected basins include all of those.

The three systems in both regions represent approximately 90 to 95% of all Hom Mali fragrant rice production of Thailand. To study the environmental impacts and eco-efficiency of Hom Mali rice, it has been deemed acceptable to ignore the remaining (in the Central Plains and Southern regions).

It is worth noting that rainfed systems in the Northeast (NE-Rw) far prevail, and represent 65% of total Hom Mali production, followed by NE-Iw (12%), N-Iw and N-Id (7% each), NE-Id (6%), and N-Rw (2%). In other words, rainfed systems far prevail in the Northeastern region, while irrigation systems prevail in the North. In terms of area, 85% of rice fields are rainfed (wet season only), 15% irrigated in the wet season, and 7% irrigated in the dry season in the Northeastern region. In the North, 81% of the fields are under controlled irrigation, most in both seasons, and 19% are rainfed (wet season only).

For sampling the cropping systems, it was chosen to ignore those proportions, and to cover all existing systems with a significant number of cases (DMUs) to allow for analysis and comparison (see section 4 on methodology).

As shown in Table 3.2, average grain yields recorded in both basins are close to the ones recorded at the regional levels, respectively. Further, the sampled cropping systems under scrutiny show similar yields as the ones at the basin and regional levels, although average yields recorded in Lam Sieo Yai basin slightly exceed both. This is partly because of prevailing irrigation and more intensive cropping conditions amongst our selected systems in the basin, favorable to higher yields, while the rest of the northeastern region is widely under rainfed, non-intensive cropping conditions. Sampling procedure is discussed further in section 4 (Methodology). The representativeness of our sample cropping systems is also discussed in section 5 (Table 5.2 and 5.3). As shown in that section, both selected basins show different cropping methods that reflect the field reality. Direct seeding has recently massively substituted traditional transplanting, due to labour scarcity issues.

Table 3.2 Average grain yields of Hom Mali rice at different geographic scales in Thailand (kg dry grain.ha^{-1})

<table>
<tr><th colspan="6">Thailand: 2281</th></tr>
<tr><th colspan="3">North: 3238</th><th colspan="3">North East: 2125</th></tr>
<tr><th colspan="3">Nam Mae Lao Basin: 3319</th><th colspan="3">Lam Sieo Yai Basin: 2219</th></tr>
<tr><th colspan="3">Average of study farms: 3487 (N=60)</th><th colspan="3">Average of study farms: 2763 (N=60)</th></tr>
<tr><th>Rainfed
3410 (N=20)</th><th>Irrigated – Dry
3415 (N=20)</th><th>Irrigated – Wet
3635 (N=20)</th><th>Rainfed
2731 (N=20)</th><th>Irrigated – Dry
2610 (N=20)</th><th>Irrigated – Wet
2948 (N=20)</th></tr>
</table>

Sources: MoAC, 2009; RID, 2009; authors’ data collection, 2011

CHAPTER 4

METHODOLOGY

This chapter introduces the methodology which can be utilized to investigate together techno-economic performances, environmental impacts and water resources use in selected rice cropping system, in order to identify more efficient and sustainable practices.

4.1 Overall framework of the study

To obtain the answers of research questions and achieve the objectives as mentioned in chapter 1, the methodology framework (Figure 4.1) is based on the LCA framework and approaches, as shown in Table 4.1. This framework starts by setting up the research hypothesis. The literature review helps to set it up and specify the study areas which were presented in chapter 3. Activities included selection of the case study, sampling, data collection, data analysis and results interpretation and dissemination as described below.

4.2 Sampling strategy and questionnaire development

The main research objects are paddy rice cropping systems, which environmental impacts and techno-economic performances are to be assessed. Efficiency analyses with DEA will consider these systems as decision making units (DMUs). As main research objects, these systems required proper sampling before data collection and analysis.

As discussed in chapter 3, it has been decided to ignore the real proportions of these systems, and rather to try and cover their diversity, for comparison sake. Also, a sufficient number of cropping systems had to be sampled, to allow for basic statistics, comparison, and cover for outliers or ill-documented cases. Limited time and means was a constraint to a larger sample.

It had been decided to keep seasons (wet and dry) separated, since grouping would not allow comparison between systems. Also, in many farms of Northeastern Thailand, plots are only cropped in wet season. Therefore, in both basins, it was decided to select 20 cropping systems (from 20 different farms) from each three main systems (Rw, Iw, Id), in both Lam Sieo Yai and Nam Mae Lao basins. This means that 120 systems were considered. As shown in Table 5.3, the sampled systems exhibit similar yields as the ones obtained at regional levels, respectively.

Table 4.2 shows the number of samples as per planting method. Since farmers now favor direct seeding against traditional transplanting, the sampling had to reflect these evolutions. Also, as shown in Table 5.1, farmers practicing rainfed rice cropping prefer direct seeding of dry seeds and that in both regions. In the North, irrigation farmers favor direct seeding of wet (pre-soaked) seeds, while in the Northeast, irrigation farmers prefer direct seeding of wet seeds. Sampling had to reflect this diversity as well.

A comprehensive questionnaire has been developed for data collection on topics of techno-economic performances, resource use and environmental impacts. It is shown in appendix A. For testing, then data collection, it was translated in Thai language. The questionnaire was formulated for data requirements on calculations of freshwater use, techno-economic performances and environmental impacts, and it was developed based on the example of the record sheet of Good Agricultural Practices (GAP) for rice which was developed by National Bureau of Agricultural Commodity and Food Standards, Ministry of Agriculture and Cooperatives. The questionnaire also contained questions on general information of farmer, the input and output to farm in each process of growing rice, labor needed, investment cost, jasmine rice production and its production costs.

The questionnaire was applied at farm level, for each cropping system that was selected. Interviews took approximately 1 hour per farmer to complete. When needed, we visited again farmers or call to them who provided incomplete information. Data collection referred to the dry and wet cropping seasons of years 2010-2011.

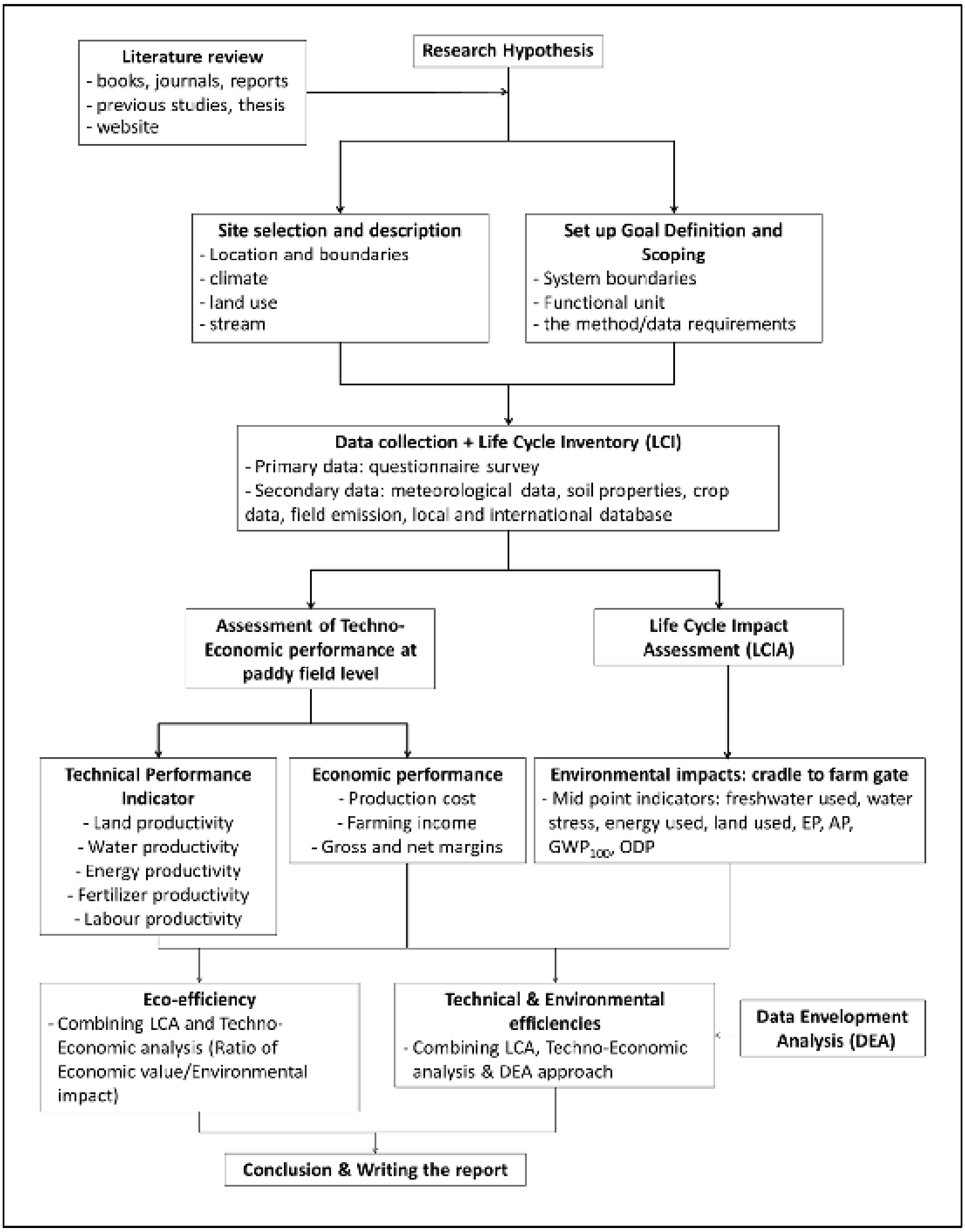


Figure 4.1 Framework of research methodology

Table 4.1 Summarization of method, indicators, data requirement and data sources based on the objectives of the study

No.	**Objective**	**Indicators**	**Method or Approach**	**Data requirement**	**Data Sources**
1	Identify and describe diverse typical Hom Mali rice cropping systems	cropping intensity, cropping calendar at basin level, crop and water management practices,	*Secondary data analysis* • Purposive sampling of study sites, looking for diversity and representativeness • Purposive and random sampling of paddy fields as DMUs *Primary data collection and analysis*	total land use for producing rice, area effectively cropped over one year, information on soil, climate, basin hydrology	Primary data at local and regional levels; secondary data
2	Analyze techno-economic performances	Yield, water use, labor, fertilizer use, pesticides use, land use, draft power use, machinery, direct energy use, production costs, net farming income (indicators expressed as per ha or as per FU)	Farmer questionnaires as per DMU, inventory and balance of mass, money and energy flows, crop budgeting	Market price, input costs, inventory of inputs used, crop and irrigation water requirements (water balance), inventory of energy and resources used (water, land)	Primary data at the farm level; secondary data
3	Assess their potential environmental impacts	Resource use indicators (freshwater used, water stress, total energy used, human energy, animal energy, fossil-energy, land used), Environmental impact categories (EP, AP, GWP_{100}, freshwater aquatic ecotoxicity, ODP)	Life Cycle Inventory. Definition of methods and calculations related to direct field emissions. Life Cycle Impact Assessment Characterization methods provided by SimaPro Calculation of mid-point indicators, Calculation of Water Stress Index, Interpretation, uncertainty analysis, sensitivity analysis	Inventory of inputs used, crop and irrigation water requirements (water balance), inventory of energy and resources used (water, land) Freshwater availability indicators at basin or local levels	Primary data at the farm level; secondary data (SimaPro, LCA databases which are adapted based on observations)

Table 4.1 Summarization of method, indicators, data requirement and data sources based on the objectives of the study (Cont'd)

No.	Objective	Indicators	Method or Approach	Data requirement	Data Sources
4	Investigate the relationship between techno-economic performances, resource use and potential environmental impact; perform efficiency analysis economic-environmental trade-off, and optimization perspectives	Indicators between environmental impacts and techno economic performances; Eco-efficiency score Joint of Indicators between environmental impacts and techno economic performances and DEA approach; Technical and environmental efficiencies	DEA approach	Indicators of objective 2 and 3	Primary data and calculations from objective 3
5	Identify and characterize best practices (efficient DMUs) towards more sustainable rice cropping systems; policy recommendations	Information on efficient and inefficient DMUs, context indicators livelihood capitals, access to markets, socioeconomic information)	Characterization of efficient and inefficient DMUs, context analysis from the DEA results	Results and indicators from Objective 4; information on the context and environment of the DMU (markets, access to resources, livelihood capitals, socio-economic information)	Primary data and calculation from objective 4; secondary data

Table 4.2 The number of samples as per planting method

Method to grow Hom Mali rice	Nam Mae Lao basin (N)			Lam Sieo Yai basin (NE)		
	Irrigated		Rainfed	Irrigated		Rainfed
	Dry Season	Wet Season	Wet Season	Dry Season	Wet Season	Wet Season
Sowing by dry seeded	5	2	14	13	15	15
Sowing by wet seeded	12	15	1	4	2	2
Transplanting (Nursery)	3	3	5	3	3	3
Total	**20**	**20**	**20**	**20**	**20**	**20**

4.3 Assessing techno-economic performances

Primary data was used to assess farm performance indicators and techno-economic performances. The techno economic performance of rice can be assessed with the help of indicators of inputs' productivities in the selected farming systems. Some indicators were cross-checked with secondary data.

The definition of ***productivity*** is “mass or value of product per unit of resource or input used”, for example; land productivity (Yield) means the mass of product per 1 ha of land used (t/ha) or water productivity means the mass of product per 1 m^3 of water used.

List of farm performance indicators can be split into technical performances and economic performances as shown in Table 4.3.

Table 4.3 Techno-economic indicators of rice production

Indicators		**Units**	**Definition**
Technical performance	Land productivity	kg/hectare	Rice mass product (kg) per area under rice crop (ha)
	Energy productivity	kg/MJ	Rice mass product (kg) per energy input (MJ)
	Fertilizer Productivity	kg/nutrients	Rice mass product (kg) per fertilizer units (kg)
	Water productivity	kg/m^3	Rice mass product (kg) per water applied (m^3)
	Pesticide productivity	kg/gram of active matter	Rice mass product (kg) per active matter (kg)
	Labour productivity	man hour	Rice mass product (kg) per labour hour (man hour)
Economic perform	Production cost	Baht/ha	Sum of all direct cost
	Gross income	Baht/ha	(Marketable rice yieldx market price) + (Saving seeds set aside x seed market price)
	Net income	Baht/ha	Gross income – Production cost

Note: marketable rice includes the rice that is self-consumed.

Source: Mushtaq et al. (2009), modified

4.3.1 Data collection for techno-economic performances

Data sources in the cropping systems analysis are crop calendars, crop management sequences, crop budgets (gross income, production costs) and production factor use (including labour, capital, inputs) and, more specifically, yields, produce market prices at the farm gate, input prices. Quantities of inputs being used were ascertained, as per cropping area basis (e.g. amount of herbicide per ha). Yield (product mass per area cropped) is crucial information since it links up land use (as the usual denominator for productivity in agro-economics) and chosen functional unit for LCA (a mass of unmilled, threshed paddy delivered at farm gate) and yield is the methodological gateway between farm economic performances and potential environmental impacts. As a consequence, special attention was put on data collection related to yields. Normally, farmers in Thailand usually do not keep record of past yields or cropping features. The research had to rely on their remembrance of previous season’s yields, and possibly of some past recent ones and cross-check with a collection of regional data which recorded by RID (Royal Irrigation Department).

Water use cannot be collected directly from field data, then calculations are needed to estimate the water consumptions. In this task, the data collection, such as meteorological data, cropping pattern data, soil data, irrigation water supply and irrigation efficiency were collected in this task. Similarly with energy use which cannot be collected directly from field data, characteristics and use, animal draft features and use, human labor were collected.

This task also includes information-gathering at watershed and regional levels, especially regarding freshwater uses, hydrology, water availability, so that water stress indicators can be processed further.

As mention earlier, there are some indicators that require both of survey and special method of calculation which are water and energy productivity indicators. The methods of assessing these indicators are mentioned as follows.

4.3.2 Calculation of Energy use

Physical energy

Physical energy is the farm of indirect energy input that is provided by the machinery and equipment used in the crop production system. The mechanical power is the main source of physical energy that used at farm. The energy used in the manufacturing, distribution and repair and maintenance are the indirect energy inputs for mechanical power source (Chamsing et al., 2006). Different farm equipment has different energy coefficients. The energy coefficients of different farm equipment are given in ผิดพลาด! ไม่พบแหล่งการอ้างอิง.

Chemical energy

The energy that is consumed during the production, processing and transportation of chemical fertilizers and pesticides fall under the category of indirect chemical energy inputs to the rice field. The total chemical energy for the fertilizers is calculated on the basis of the respective percentage of the Nitrogen (N), Phosphorus (P_2O_5) and Potassium K_2O present in respective fertilizer. The energy coefficient of N, P_2O^5 and K_2O are shown in table 4.5. In order to control the weed, insects and pest attack as well as to control the weeds insecticides and pesticides are used. Table 4.6 shows the energy equivalent (kWh/L)

Biological energy

Among the biological energy seed and the hormones are the main biological energy inputs and fall under the category of indirect input in rice cultivation. The energy equivalent of rice seed is 14.7 MJ/ha which was mentioned by Nassiri and Singh (2009). The average seed rate reported by Blengini & Busto (2009) in Vercelli, Italy is 200 kg/ha and 93.75 and 125 kg/ha are reported by farmers interview in Lam Sieo Yai and Nam Mae Lao basins, Thailand.

Calculation of total energy use

The total energy use can be calculated as follow.

$$\begin{aligned}\text{Total Energy use (MJ/ha)} &= \text{Labour Energy} + \text{Animal Energy} + \text{Mechanical Energy} + \text{Seed Energy} \\ &+ \text{Equipment Energy} + \text{Fertilizer Energy} + \text{Chemical Energy}\end{aligned}$$

- Human labour energy

The human labour (man hours) was converted into energy units by multiplying the number of total human labour (family and hire labour) with working hours to the energy coefficient. The energy equivalent of an adult man is 1.97 MJ/h and for an adult woman it is 1.57 MJ/ha. The following equation was followed for the conversion of physical unit of human labour into energy unit.

$$\text{Human labour (MJ/ha)} = \frac{\text{Wh} \times \text{Hl} \times \text{En.Eqr}}{\text{Planted area}}$$

where;

Wh = Total working hours of human labour
Hl = Total human labour
En. Eqr = Energy equivalent of human labour

- Animal energy

The animal hour was converted into energy units by multiplying the number of total animals with working hours to the energy coefficient. The energy equivalent of the animal is based on the activity (see table 4.4). The following equation was followed for the conversion of physical unit of animal draft into energy unit.

$$\text{Animal Energy (MJ/ha)} = \frac{\text{Wh} \times \text{Hl} \times \text{En.Eqr}}{\text{Planted area}}$$

where;

Wh = Total working hours of animal draft
Hl = Total animals
En. Eqr = Energy equivalent of animal draft

- Mechanical energy

Mechanical energy inputs were calculated based on the fuel consumption (liter/hour) of the machinery, types of machinery and working hours per operation as well as the number of operations in the rice planted area. The fuel consumption data were collected with field survey. The following equation allows for the conversion of physical unit of machinery use into energy unit.

$$\text{Mechanical energy (MJ/ha)} = \frac{\text{Fc} \times \text{No.} \times \text{Wh} \times \text{days} \times \text{En.Eqr}}{\text{Planted area}}$$

where;

Fc = Fuel consumption
No = Number of the farm machinery
Wh = Total working hours of machinery
En. Eqr = Energy equivalent of fuel (MJ/L).
(48.23 MJ/L for gasoline and 56.3MJ/L for diesel)

- Seed energy

The following equation was followed to convert the physical unit of seed into energy unit. The energy conversion factor of seed is 14.7 MJ/kg.

$$\text{Seed Energy (MJ/ha)} = \frac{\text{Seed (kg/ha)} \times \text{Energy equivalent}}{\text{Cultivated area}}$$

Table 4.4 Energy coefficient (MJ/h) of various farm equipment's

Power Source	Equipment	Energy coefficient (MJ/h)
Manual	Spade	0.314
	Spickle	0.031
	Sickle	0.836
	Bund former	0.502
	Sprayer	0.502
	Wheel hand hoe	0.502
Animal	Plough	0.627
	Cultivator	1.881
	Disk harrow	3.135
	Planter	1.568
	Seed drill/planter	1.254
	Puddler	1.254
	Bund former	1.442
	Cart	5.204
	Toka	1.29
Tractor	M.B. Plough	2.508
	Cultivator	3.135
	Disk Plough	3.762
	Planter	9.405
	Disk harrow	7.336
	Seed drill/planter	8.653
	Leveler	4.703
	Bund former	2.063
	Reaper	5.518
	Puddler	2.508
	Rotavator	10.283
	Trailer	17.431
	Combine harvester	47.025
Others	Thresher/sheller	7.524
	Power toka	1.568
	Centrifugal pump	1.75
	Electric motor 35 hp	0.343
	Electric motor (others)	0.216
	Diesel engine	0.581
	Tractor 45 hp & above	16.416
	Tractor (lower than 45 hp)	10.944
	Self propelled combine	171

Source: Nassiri and Singh, 2009

- Fertilizer energy

The fertilizer energy inputs were calculated by multiplying the respective energy equivalents of (N, P and K) as shown in table 4.5 to their respective percentage ingredients in the compound fertilizers used per unit area. The sum of the energy of all the ingredients (N, P K) will give the fertilizers energy use per unit area.

$$\text{Fertilizer energy input} = \frac{\text{Fertilizer (kg/ha)} \times \text{\% N, P, K}}{100}$$

$$\text{Energy of N, } P_2O_5\text{, K2O} = \frac{\text{Share of N, } P_2O_5\text{, K2O} \times \text{Energy equivalent}}{\text{Planted area}}$$

$$\text{Total energy input of fertilizer (MJ/ha)} = \text{N (MJ/ha)} + P_2O_5 \text{ (MJ/ha)} + K_2O \text{ (MJ/ha)}$$

- Pesticides, herbicides and other chemical energy inputs

The energy equivalent of the different chemicals was calculated by multiplying the respective energy equivalents with the quantity of the chemical used (liter or kg/rai). The energy equivalent can be seen from table 4.6

$$\text{Chemical Energy (MJ/ha)} = \frac{\text{Amount of chemical (L or kg)} \times \text{Energy equivalent}}{\text{Application area}}$$

Table 4.5 Energy coefficient (MJ/kg) of various fertilizers

Fertilizer	Energy coefficient (MJ/kg)
Nitrogen(N)	60.60
Phosphorus (P_2O_5)	11.10
Potassium K_2O	6.7

Source: Mushtaq et al., 2009

Table 4.6 Energy coefficient (MJ/kg) of various fertilizers

Type of chemical	energy coefficient (Kwh/L)
Insecticides	55.5
Herbicides	66.7
Fungicides	17.2
Molluscicides	28.1

Source: Mushtaq et al., 2009

4.3.3 Assessing fresh water use by crops

Freshwater use is calculated from evaporative water basis, as the sum of the evaporation of rainfall and stock in soil from crop land (green water use) and the evaporation of irrigation water from crop land, including all losses (blue water use); it excludes the non evaporative use (grey water use). The method to calculate freshwater use is mentioned below.

This study decided to use virtual water (VW) and water footprinting concept to calculate the total water use. As mentioned in the previous section, VW in agricultural sectors, which consists of green water use (WU_g), blue water use (WU_b) and grey water use (WU_{gr}) but only WU_g and WU_b are the water taken by the plant. For WU_{gr} is only an impact produce by irrigation system and agricultural production due to pollutant load. Therefore, in this study WU_g and WU_b were calculated and represented as freshwater use by crops. There are the assumptions about the application of WU_g and WU_b in agricultural area which are only WU_g was considered in agricultural area which under rain-fed condition and natural crop such as forest area and both WU_g and WU_b were considered in irrigated-agricultural areas.

Calculation of green water use by field crops

As mentioned, WU_g can be described that the volume of water is taken by the plants from the soil, which is originating from the infiltrated rain water. WU_g can be expressed as "Effective rainfall" which is different among the type of crop and the method of irrigate water, such as the effective rainfall of rice is water that remains in paddy fields at the safety level to rice. The effective rainfall can be calculated by using many methods such as a fixed percentage of rainfall, dependable rainfall, empirical formula, USDA Soil Conservation Service method and water balance. There are some assumptions for calculation of effective rainfall, which is the amount of effective rainfall is an input to agricultural areas and natural crop area and all of effective rainfalls are used by crop. This study decided to calculate WUg of all types of crops except rice by using USDA Soil Conservation Service method that is included in CropWat model. This method can be according to formulas are shown below.

$$\begin{aligned} P_{eff} &= \frac{P_{month} \times (125 - 0.2 \times P_{month})}{125}; && \text{for } P_{month} \le 250 \text{ mm} \\ P_{eff} &= 125 + 0.1 P_{month}; && \text{for } P_{month} > 250 \text{ mm} \end{aligned} \qquad \text{(equation 4.1)}$$

Where; P_{eff} is WU_g or effective rainfall (mm) and P_{month} is monthly rainfall in mm. P_{month} minus P_{eff} can be called the runoff which are not used by crop.

Calculation of blue water use by field crops

WU_b is the volume if water taken by the plant which is supplied by irrigation and also includes water used for processing and other post-harvest activities. The irrigated water is calculated from the crop evapotranspiration until harvest. For all crops except rice, a model based on CROPWAT by the Food and Agriculture Organization of the United Nations (FAO) was used as the tool to calculate WU_b in the agricultural sector which can be called crop water requirement. CROPWAT is a computer model which simulates crop and irrigation water requirements from meteorological data, soils and crop data. In this approach, potential evapotranspiration or reference crop evapotranspiration (ETo) is estimated using the Penman-Monteith method as recommended by FAO (1992). Each parameter in this formula is determined from meteorological data sets. After model calculate ETo, and then the model will calculate actual evapotranspiration (ETa) based on by the crop coefficient (Kc) and followed by an estimate crop water requirement and irrigation requirement. Penman-Monteith method derived as below.

$$ET_0 = \frac{(0.408\Delta R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.034 u_2)} \qquad \text{(equation 4.2)}$$

Where ET_0	is reference crop evapotranspiration	[mm/day]
R_n	is net radiation at the crop surface	[MJ m^{-2} day^{-1}]
G	is soil heat flux density	[MJ m^{-2} day^{-1}]
T	is mean daily air temperature	[°C]
u_2	is wind speed at 2-m height	[m/s]
e_s	is saturation vapor pressures	[kPa]
e_a	is actual vapor pressures	[kPa]
Δ	is slope vapor pressure curve	[kPa/°C]
γ	is psychometric constant	[kPa/°C]

Adaptation to paddy rice: Calculation of effective rainfall and irrigation requirements of rice

As mentioned, in this study WU_g and WU_b were calculated and represented as freshwater use by crops. Total water use of rice production can be calculated as shown in Table 4.7

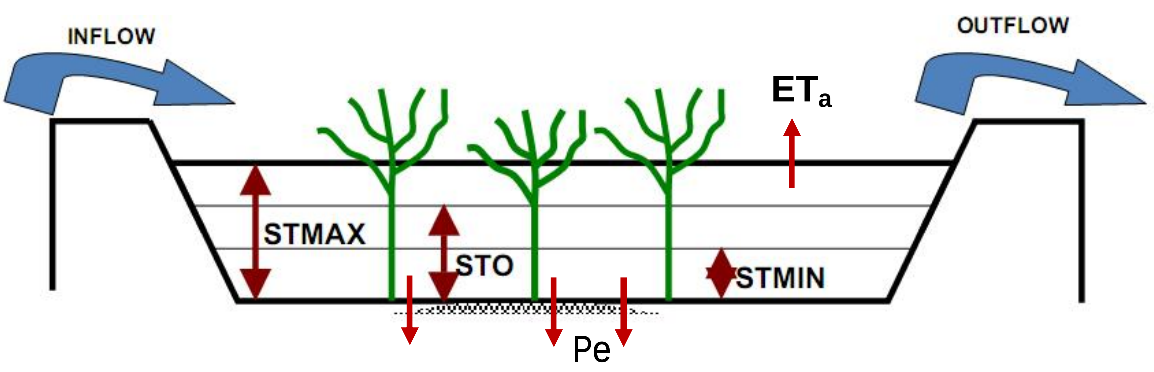
Table 4.7 Framework of total water use of rice productions

Type of water use			Source	Method to calculate
Amount of Water Use	**Green water**	Effective rainfall	Precipitation	Water Balance
	Blue Water	Water for soaking seeds	IRW & WN	Analysis based on primary data
		Water for land preparation	IRW & WN	Analysis based on primary data
		Water for crop	IRW & WN	(1st priority) Analysis based on primary data
				(2nd priority) Calculation based on water needed
		Water for mixing chemical	IRW & WN	Analysis based on primary data

Notice: IRW is irrigation water and WN is a water from natural sources (ponds and small canals)

Effective rainfall is the rainfall that able to use by crop and it is different among the type of crop and the method of irrigate water, such as the effective rainfall of rice is water that remain in paddy fields at the safety level to rice. Effective rainfall model is the model for calculation of rainfall that can be used instead of irrigated water, which based on the amount of rainfall at each time step, crop water requirement, percolation and the height of the bund. Water balance concept in the paddy field is applied to effective rainfall model and it has been used in WUSMO which developed by Kasetsart University.

There are some assumptions for calculation of effective rainfall, which is the amount of effective rainfall is an input to the paddy field and all of effective rainfalls are used by crop (Hom Mali rice). Condition of effective rainfall and irrigation requirement model are described below. As Figure 4.2, water levels in paddy field for calculation of effective rainfall were set (STMAX, STO and STMIN). These water levels were set based on the samplings.



STMAX = maximum water level
STO = medium water level = water level after supply irrigated water
STMIN = minimum water level = water level for starting supply irrigated water
Pe = percolation
ET_a = actual evapotranspiration

(Modified by author)

Figure 4.2 Water levels in paddy field for calculation of effective rainfall

Certain parameters in this model are worth-mentioning:

R_n = rainfall depth at day n in mm
St_{n-1} = water level in paddy field at starting day n
St_n = water level in paddy field at ending day n
ETa = actual evapotranspiration (mm/day) at day n
= Kc x ETo
where Kc = crop coefficient
ETo = potential evapotranspiration or reference crop evapotranspiration (mm/d)

Potential evapotranspiration or reference crop evapotranspiration (ETo) is mentioned in the previous section.

St_n can be calculated by

$$St_n = St_{n-1} + R_n - ETa - Pe$$

1st condition: If $St_n > STMAX$
$Re = STMAX + ETc + Pe - St_{n-1}$
$Stn = STMAX$

2nd condition: If $St_n <= STMAX$ and $St_n >= STMIN$
$Re = R_n$
$St_n = St_n$

3rd condition: If $St_n < STMIN$
$Re = R_n$
$St_n = STO$

St_n can be changed to STO by supply the irrigated water to the paddy field.

Therefore; the irrigation requirement (Irr) can be calculated as followed.

$$\text{Irr} = \frac{\text{the changing depth from } St_n \text{ to STO - Re}}{\text{irrigation efficiency}}$$

According to field observations, the parameters of the model which are STMIN, STO and STMAX can be set as follows.

STMIN = 45 mm
STO = 90 mm
STMAX = 150 mm

Percolation rate was set based on secondary data at 1.5 mm/day for Nam Mae Lao basin and 2.0 mm/day for Lam Sieo Yai basin.

To produce Hom mali rice, water is needed for some activities such as water for soaking the seeds (for wet seeding method), land preparation, crop water use and mixing the chemical, and water sources can be irrigation system (surface water) and natural water resources (precipitation). Therefore, this study decided to include all the water use from an irrigated system and natural water resources into WU_b as shown in Table 4.7.

4.4 Calculation of Green Water use (WUg) and Irrigation requirement

Meteorological data sets and crop coefficient were collected from RID and MET. Actual evapotranspiration (ETa) can be calculated according to Penman-Monteith method. Table 4.12 and Table 4.9 show the total actual evapotranspiration of each rice cropping system. In both selected basins, ETa in the dry season is higher than in wet season, and ETa of transplanting method is higher than ETa of direct seeding methods because dry season is longer, and transplanting requires nursery time which adds further time to the production cycle. The comparison of ETa between regions shows that ETa in the Northeast region is higher than the North region because of climatic and soil conditions.

Table 4.8 Actual evapotranspiration of rice cropping system (direct sowing methods) in selected basins (year 2010)

Rice cropping system			**Duration**	**Actual Evapotranspiration (mm)**
Region	**Season**	**Water condition**		
North (Nam Mae Lao basin)	Wet	Rainfed	July - October	480.4
	Wet	Irrigated		
	Dry	Irrigated	Feb - May	653.9
Northeast (Lam Sieo Yai Basin)	Wet	Rainfed	July - October	542.1
	Wet	Irrigated		
	Dry	Irrigated	Feb - May	668.8

Table 4.9 Actual evapotranspiration of rice cropping system (transplanting method) in selected basins (year 2010)

Rice cropping system			**Duration**	**Actual Evapotranspiration (mm)**
Region	**Season**	**Water condition**		
North (Nam Mae Lao basin)	Wet	Rainfed	Jun - October	573.6
	Wet	Irrigated		
	Dry	Irrigated	Jan - May	726.5
Northeast (Lam Sieo Yai Basin)	Wet	Rainfed	Jun - October	645.9
	Wet	Irrigated		
	Dry	Irrigated	Jan - May	753.9

Table 4.10 and Table 4.11 show the effective rainfall (Green Water use) and irrigation requirement of each rice cropping system. The effective rainfall in the wet season of both basins are not quite different, but in the dry season the effective rainfall in Nam Mae Lao is higher than Lam Seio Yai basins. The irrigation requirement of Northeast region is higher than the irrigation requirement of North region both in wet and dry seasons. In the wet season, the irrigation requirement of north region shows 0 mm, it means there is no need to supply the irrigated water into the paddy field because the effective rainfall is higher than actual evapotranspiration and percolation loss.

4.5 Assessing environmental impacts

As described in the literature review chapter, joint LCA and techno-economic analyses were applied in this research. The research collected analyses and combined indicators of techno-economic performances (rice production, costs, and product value) with environmental impact indicators based upon the life cycle approach. Both approaches apply at the same plot level (cropping system level) and complement each other. Techno-economic analysis typically results in monetary values as per factor of production (e.g. labour, land, agro-chemicals) while LCA expresses environmental impacts as per selected functional units. Techno-economic analysis is described in a previous section, and the LCA approach is described below.

4.5.1 System definition

The LCA methodology is used to evaluate the environment impact of rice farming. According to ISO 14040 (2006), there are four main stages of LCA: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of the result. This task mainly describes about the first phase of LCA which apply to Hom Mali rice production chain in Thailand.

Table 4.10 Effective rainfall and irrigation requirement of rice cropping system (wet and dry seeded method) in selected basins

Rice cropping system			**Total Rainfall**			**Actual Evapotransipiration**	**Irrigation Requirement**
Region	**Season**	**Water condition**	**Duration**	**Average Total Rainfall (mm)**	**Total Effective Rainfall (mm)**	**(mm)**	**(mm)**
North (Nam Mae Lao basin)	Wet	Rainfed	July - October	1372.2	678.4	480.4	-
	Wet	Irrigated					0
	Dry	Irrigated	Feb - May	262.3	262.3	653.9	467.2
Northeast (Lam Sieo Yai Basin)	Wet	Rainfed	July - October	896	740.1	542.1	-
	Wet	Irrigated					0
	Dry	Irrigated	Feb - May	191.56	191.56	668.8	539.1

Table 4.11 Effective rainfall and irrigation requirement of rice cropping system (transplanting method) in selected basins

Rice cropping system			**Total Rainfall**			**Actual Evapotransipiration**	**Irrigation Requirement**
Region	**Season**	**Water condition**	**Duration**	**Average Total Rainfall (mm)**	**Total Effective Rainfall (mm)**	**(mm)**	**(mm)**
North (Nam Mae Lao basin)	Wet	Rainfed	Jun - October	1538.8	776.1	573.6	-
	Wet	Irrigated					0
	Dry	Irrigated	Jan - May	262.5	262.5	726.5	544.1
Northeast (Lam Sieo Yai Basin)	Wet	Rainfed	Jun - October	1018.2	801.9	645.9	-
	Wet	Irrigated					46.5
	Dry	Irrigated	Jan - May	199.9	199.9	753.9	620.3

4.5.2 Set up goal and scoping

The main aim of this study is to assess rice cropping systems of selected basin in Thailand with regard to their potential environmental impacts, including resource use and technical and economic performance, in order to further investigate the relationship between them and finally to identify best compromise practices to optimize the system (maximizing the economic return at farm level from production and minimizing the environmental impact). For this purpose different rice cropping systems with different intensification level, mechanization are analyzed. The differences in the environmental impacts and the resource consumption of selected rice production systems are analyzed in the present study.

The goal of this study is to analyze the production practices of rice cultivation in order to assess the energy consumption, water use in the field operations during the growth period of rice crop. The production and handling of the main inputs either imported or locally produced are considered as the part of the system, and estimated through existing LCA databases. The emission as a result of the application of the inputs and the direct field emission which occurs during growing period are considered as the part of the system. The technical performances of the rice production systems are analyzed in order to investigate the rice yield per unit of input consumed or the land used. Total cost at farm level and the farm gate revenue are determined in order to assess the cost and income per one kilogram of paddy rice respectively, in order to assess the economic performance of rice production systems. The analysis of the differences of environmental impacts and the techno economic performances of all the systems were performed keeping in view the system boundary as shown in Figure 4.3.

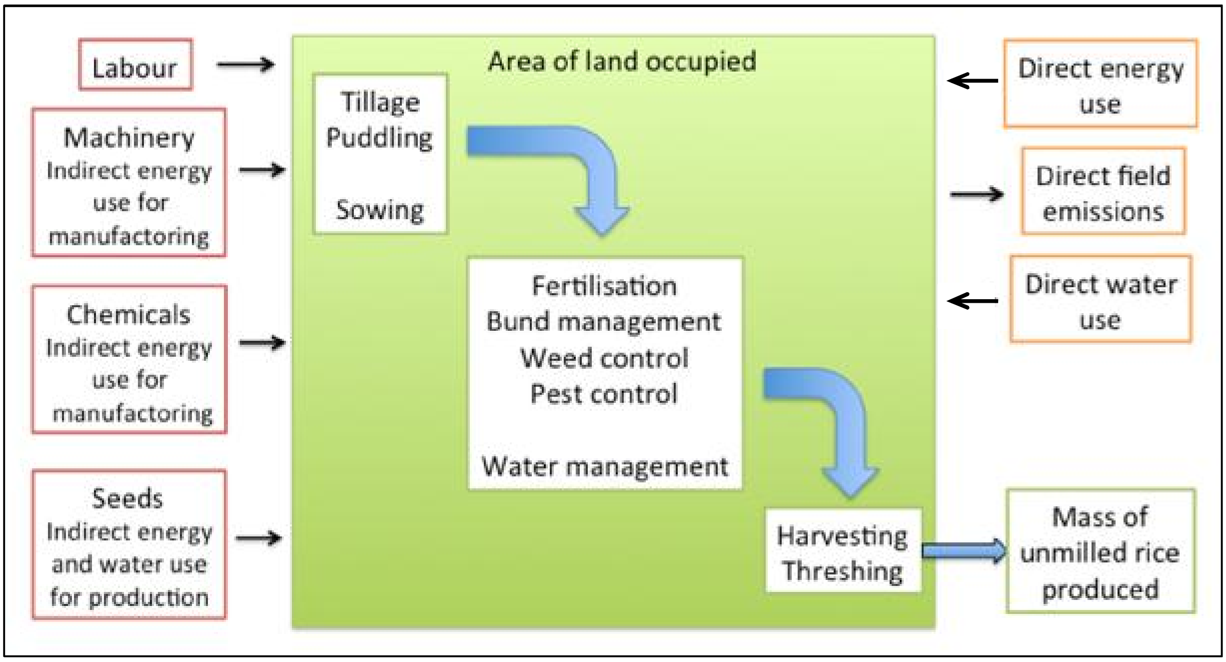


Figure 4.3 System boundary of rice cropping systems

4.5.3 System boundary

The LCA was carried out cradle-to-farm gate which can be represented by agricultural process. This study focus on only cradle-to-farm because many studies (Yossapol et al., 2008; Hokazono et al., 2009; Blengini & Busto, 2009; Kasmaprapruet et al., 2009) concur that most impacts occur at field and pre-field levels; in particular, global warming potential is mainly influenced by field emissions and paddy field emissions has great influence on key indicators (GWP, AP, EP POCP). Another reason is that techno-economic performance analysis is limited to the farm level. The sequences of activities were performed based on this system and the details of the system are described as follows.

Figure 4.3 represents the details of agricultural process which were set up based on the interviewing with farmers in the north and northeast of Thailand. The starting of agricultural process is land preparation and followed by the method to grow Hom Mali rice. In Thailand, there are two methods to grow rice, which are transplanting and sowing (broadcasting). Before transplanting, farmers have to do the nursery which has to prepare the nursery land by tillage and then sow the rice seed, but rice seed have to be soaked in water before sowing and then wait for small rice grow up. After small rice grow and then farmers can transplant to the paddy field. Another method to grow rice is sowing; famers no need to do the nursery. Hom Mali rice production takes time around six months between planting and harvesting. During the growing period, to get good yields, normally farmers in Thailand need to do fertilizer application, pest management and weed management by applying fertilizers, pesticides, herbicides, fungicides, insecticides and raticides. During the growing period also release direct air emission such as methane, nitrous oxide and ammonia, as well as, emissions of phosphorus and nitrates to water.

4.5.4 Functional unit

One of the primary purposes of a functional unit (FU) is to provide a reference to the input and output data (in a mathematical sense). As shown in literature review, most agri-food LCA research has been using mass unit of product. It is suggested we consider.

1 kg of paddy Hom Mali rice delivered at farm gate, unprocessed, dried at about 15% water content, as the main functional unit for LC analysis. For techno-economic analysis, it may prove interesting to also report results as per area unit, resource or input use units since productivities of factors of production are crucial information.

4.5.5 Identify mid-point impact indicators

The mid-point impact indicators were addressed in this task which can be split into two groups.

First group

The first group is resource use indicators (or input-related), i.e.,

- Energy uses

  This impact category is used as an indicator of the total energy resource consumption. Energy uses split into human, animal draft, fossil, non-fossil energies.
- Freshwater resources use
- Land use

Second group

The second group is environmental impact categories (or emission-related indicators), i.e.,

- Eutrophication

  Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. The Nutriphication Potential (NP) is set at 1 for phosphate (PO_4). Other emissions also influence eutrophication, notably nitrogen oxides and ammonium.

- Acidification

  The Acidification Potential (AP) is expressed relative to the acidifying effect of SO_2. Other known acidifying substances are nitrogen oxides and ammonia. SO_x has been added, with the same value as SO_2.
- Global warming potential

  The Global Warming Potential (GWP) is the potential contribution of a substance to the greenhouse effect. This value has been calculated for a number of substances over periods of 20, 100 and 500 years because it is clear those certain substances gradually decompose and will become inactive in the long run. Normally, GWP over a 100-year period is used in many researches because this is the most common choice.
- Freshwater aquatic ecotoxicity

  Substances in this class are given values for toxicity to freshwater. The main substances are heavy metals. Values have been established for emissions to water.

4.5.6 Life cycle impact assessment (LCIA) method

The LCIA method of the research is “characterization method” which is the translation of a pollution or emission into an environmental impact. For instance, chemical fertilization leads to amounts of nitrate and phosphate leaching; characterization methods translate such amounts into mid-point indicators such as eutrophication. This research focused on mid-point indicators listed in Table 4.12. Rice is a main contributor to CH_4 anthropogenic emissions, so Global Warming Potential (GWP) is to be assessed. The results of many researches of LCA in rice production (Yossapol et al., 2008; Hokazono et al., 2009; Blengini & Busto, 2009; Kasmaprapruet et al., 2009) show that GWP is mainly influenced by direct field emissions, which also have the greatest impact on three other indicators (AP, EP POCP). Paddy rice systems are actually aquatic ecosystems with wide ranging relationships with other systems owing to massive water flows, therefore aquatic toxicity is to be assessed. Table 4.13 shows the possible characterization model and its impact category of producing rice, which related to this research. All the indicators used in this study are typical indicators mentioned in many studies of LCA of rice production system (Yossapol et al., 2008; Hokazono et al., 2009; Blengini & Busto, 2009; Kasmaprapruet et al., 2009) and of other productions.

The specific software used for the purpose of LCIs computation is SimaPro7.3. The CML baseline 2000/world, 1995 methodology is typically used to find out midpoint impact indicators. Therefore this study also used CML to estimate mid-point indicators. The idea of the research was to provide a range of indicators of environmental impacts (mid-point indicators), and not to reach end-point indicators or single scores, so that the rice and irrigation community, unfamiliar with LCA approaches, would follow more easily the process towards eco-efficiency analysis. The CML method was deemed sufficient.

The method to calculate the energy use was mentioned in this section. In this study decided to use the energy inputs-outputs concept where the total energy in-outs can be called “Total energy use”. There are three main groups of energy inputs, namely physical, chemical and biological energy and each agricultural input has its own energy equivalent (Ullah, 2009). These energy inputs may be on the farm of chemicals (fertilizers and pesticides), human labour, animal labour and machinery power or it may be in the farm of fossil fuel, water and seed. All input parameters were collected during field survey communications with farmers.

Table 4.12 Commonly Used Life Cycle Impact Categories

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Common Possible Environmental impact categories	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrous Oxide (N_2O) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrous Oxide (N_2O) Nitrates (NO_3) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Freshwater aquatic ecotoxicity	Global	Emission of toxic substance to air, water and/or soil	Freshwater aquatic ecotoxicity potential (FAETP)	Converts LCI data to kg (1,4-dicholorobenzenz equivalents)
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Deprivation Potential (Pfister et al., 2009)	Multiply water use by WSI

(Source: EPA's 2006 Document by Mary Ann Curran)

Table 4.13 Characterization model and impact categories of rice production systems (Agricultural process)

Production Phase	Subsystem	Input to system	Examples of LCI Data (i.e. pollutant , emission)	Common Possible Environmental impact categories and resource use indicators
Agricultural process	• All the processes	• Land use	Land used or consumed	Land used
	period of rice • Water management • Harvesting • Threshing	• Mechanical field operation	Carbon Dioxide (CO_2)	Global Warming Potential (GWP)
	• Fertilizer application	• N Fertilizer	nitrous oxide (N_2O)	
	• Growing period (Field emissions)	-	Methane (CH_4)	
	• Fertilizer application	• N Fertilizer	Nitrogen Oxides (NOx)	Acidification Potential (AP)
	• Pest management • Weed management	• Chemical ingredients	Sulfur Oxides (SOx) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF), Ammonia (NH4)	
	• Fertilizer application	• P Fertilizer • N Fertilizer	Phosphate (PO_4) Nitrogen Oxide (NO) nitrous oxide (N_2O)	Eutrophication Potential (EP)
	• Pest & weed management	• Chemicals ingredients	Nitrates Ammonia (NH_4)	
	• Pest management • Weed management	• Chemical ingredients	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH3Br)	Ozone Depleting Potential
	• Land preparation • Water management • Harvesting • Threshing	• Mechanical field operation (Fuels consumption)	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential
	• Pest & weed management	• Equipment such as sprayer (Fuels consumption)		
	• Growing period	• Crop water requirement • Irrigation requirement	Water used or consumed	Water used or consumed
	• All the processes except growing period of rice	• Labor and animal draft • Mechanical used • Equipment used	Energy used or consumed	Energy used or consumed

Assessing of Water stress index (WSI) and water deprivation potential

WSI, many calculation methods are available as shown in Table 2.2; only one method was considered and applied to study areas: the method of Pfister et al. (2009);

It was decided to select Pfister et al. (2009) method because it takes into account water use, hydrological water availability and variation of monthly & annual of precipitation because Thailand is tropical area which rainfall is dominated parameters and it can lead to increase water during a specific period (dry season).

The method of calculation for WSI based on Pfister et al. (2009) was mentioned in section 2.6. In 2009, Pfister et al. commented on WSI which calculated by using WaterGAP2 model based on the WTA ratio (Alcoma et al., 2003) that the hydrological water availability modeled in WaterGAP2 is annual average based on climate data (1961-1900). However, both monthly and annual variability of precipitation may lead to increase water stress during a specific period, if only insufficient water storage capacities are available or if much of the stored water is evaporated. To correct for increased effective water stress, they introduced a variation factor (VF) to calculate a modified WTA (WTA*) which differentiates watersheds with strongly regulated flows (SRF) as defined by Nilsson et al. (2005). VF is the aggregated measure of dispersion of the multiplicative standard deviation of monthly (S^*_{month}) and annual precipitation (S^*_{year}).

After calculation of WSI, it is used to calculate water deprivation potential from the multiplication of blue water with WSI.

Assessing of human water use

The Basic Human Water Requirements

Gleick (1996) developed a water scarcity index as a measurement of the ability to meet all water requirements for basic human needs: drinking water for survival, water for human hygiene, water for sanitation services, and modest household needs for preparing food. The proposed minimum amount needed to sustain each is as follows:

- Minimum Drinking Water Requirement: Data from the National Research Council of the National Academy of Sciences was used to estimate the minimum drinking water requirement for human survival under typical temperate climates with the normal activity is about 5 liters per person per day.
- Basic Requirements for Sanitation: Taking into account various technologies for sanitation worldwide, the effective disposal of human wastes can be accomplished with little to no water if necessary. However, to account for the maximum benefits of combining the waste disposal and related hygiene as well as to allow for cultural and societal preferences, a minimum of 20 liters per person per day is recommended.
- Basic Water Requirements for Bathing: Studies have suggested that the minimum amount of water needed for adequate bathing is 15 liters per person per day (Kalbermatten et al., 1982; Gleick 1993).
- Basic Requirement for Food Preparation: Taking into consideration both developed and underdeveloped countries, the water use for food preparation to satisfy most regional standards and to meet basic needs is 10 liters per person per day.

According to the basic of human water requirements, total water requirement of human use is 50 liters per person per day (0.05 m^3/person/day). Both Falkenmark and Gleick developed the “benchmark indicator” of 1,000 m^3 per capita per year as a standard that has been accepted by the World Bank (Gleick 1995; Falkenmark and Widstrand 1992). This study decided to use 50 liters per person per day as the basic human water requirements.

Therefore; the annual water requirement for human use (W_{hu}) can be calculated as followes;

$$W_{hu} = DP \times A \times BHWR \times day \qquad \text{(equation 4.3)}$$

Where; DP = Density of population (person per km^2)
A = Area (km^2)
BHWR= Basic human water requirements (0.05 m^3/person/day)
day = 365 days

The density of population in Lam Sieo Yai basin is about 166.23 persons per km^2 and Nam Mae Lao basin is about 102.32 persons per km^2 (Department of Provincial Administration, 2010).

4.5.7 Data collection

Required data for calculation of actual evapotranspiration (ETa)

As previous mentioned, the equation of Penman-Monteith can be used as a tool to estimate ETa. Table 4.14 shows their data requirement and sources.

Table 4.14 Data requirement to estimate actual evapotranspiration (ETa)

Parameter	Data Type	Specified Data	Sources	Unit
Meteorological data	Air Temperature	Monthly means of minimum and maximum temperature	TMD	°C
	Relative humidity	Percent relative humidity (Mean monthly)		%
	Sunshine duration	Monthly means sunshine duration hours		Hours
	Wind speed	Wind speed at 2 m height		m/s
	Rainfall	Mean monthly rainfall		mm
Soil data	Soil type, soil texture	-	RID, LDD	-
	Infiltration data	Maximum infiltration rate	RID	mm/day
Crop data	Crop coefficient (Kc)	-	RID, FAO	
	Crop development stage		RID, FAO, Rice Department	
	Cropping Pattern	Field data	Rice Department, Communicate with farmer	

Where; TMD is Thai Meteorological Department, RID is Royal Irrigation Department, LDD is Land Development Department, and FAO is Food and Agriculture Organization (United Nations)

Required data for estimation of the environmental impact

Table 4.15 shows the summarization of the data sources of inventory data in different processes which can be divided into primary data and secondary data. The primary was collected by interviewing with farmers, agronomists and rice processing technicians. The crop management or rice cropping at farm level practices was investigated by interviewing the farmers. The inventory data at this level comprise the energy uses, applications of pesticides, herbicides, fungicides, raticides, fertilizers (both chemical and organic), machineries (capital goods) and equipment used. It also includes irrigation system and other infrastructures and water management or flooding practice. The data relevant to direct emissions from the paddy field which are difficult to measure. Therefore, the literature reviews which have to focus on local (Thailand) references were used. From the inventory data for the energy and transport system were retrieved from the international database (Ecoinvent database).

Table 4.15 Data sources of inventory data

Production Phase	**Subsystem**	**Data sources**	
		Primary data	**Secondary data**
Agricultural process	• Land preparation	• Mechanical field operation • Labor and animal draft	• I/O fuel production and emission from fuel combustion
	• Fertilizer application	• Name of fertilizer • Application rate • Active ingredients • Total use • Machinery or equipment • Fuel consumption	• I/O chemical production • I/O fuel production and emission from fuel combustion
	• Pest management	• Name of pesticides/chemical • Application rate • Active ingredients • Total use • Machinery or equipment • Fuel consumption	• I/O chemical production • I/O fuel production and emission from fuel combustion
	• Weed management	• Name of chemical • Application rate • Active ingredients • Total use • Machinery or equipment • Fuel consumption	• I/O chemical production • I/O fuel production and emission from fuel combustion
	• Water management	• Machinery or equipment	• I/O fuel production and emission from fuel combustion • I/O electricity production
	• Harvesting	• Labor • Machinery or equipment	• I/O fuel production and emission from fuel combustion
	• Threshing	• Labor • Machinery or equipment	• I/O fuel production and emission from fuel combustion
	• Field emission	-	• Literature review

Where; I/O stands for input and output.

4.5.8 Life Cycle Inventory (LCI)

Life cycle inventory (LCI) is the second phase of LCA. Field work and data collection were being carried out in this task. The data collection based on the method that described in task 1 and applied at systems under investigations, namely cradle-to-farm gate.

LCI consisted of quantifying the flow models which related to functional units and resulting in emissions or resource consumption. In practice, this task involves data collection for all inputs and outputs, computation amounts of these inputs and output based the functional units. Many data which mentioned in Table 4.15 were collected and inventory focused on to energy use (including human labor and animal draft), land use, applications of fertilizers (chemical and organic), pesticides, herbicides, fungicides, insecticides, raticides, machinery, water management (flooding practices) and equipment used, e.g. farm built environment and infrastructure which including irrigation systems.

LCI was conducted by making use of data collection plans, tools and methods which defined in task 1 and applied to case study situations (study areas) which defined in Chapter 3.

As mentioned above the rice is a main contributor to CH_4 anthropogenic emissions and also other direct emissions during the growing period. To measure the direct emission in the paddy field is difficult and take time. Therefore, in this study, the methods to estimate the direct emissions were finalized as shown below.

The most important and impacting direct field emissions in paddy rice production include air emissions of methane, nitrous oxide, nitrogen oxides, and ammonia, as well as emissions of phosphorus and nitrates to water. Also, pesticides losses occur. Therefore, the direct field emissions (as previous mentions) were included in this chapter. Carbon dioxide is considered neutral; heavy metals and other potential pollutants have been ignored.

4.5.9 Direct field emissions

This research took account of Methane (CH_4), Nitrous oxide (N_2O), Nitrogen Oxide (NO), Ammonia (NH_3) (emissions to air), Nitrates and Phosphorus emissions (to water) and pesticides emissions (to water and soil). CH_4, N_2O, NO and Ammonia (NH_3) were calculated by adjusting the daily background emissions with scaling factor and the real practices in the fields (application of chemical inputs). The daily background emissions were suggested by Yan et al. (2003b) after literature review. Total emissions were calculated by the adjusted daily emissions multiplied by the number of days under cultivation. 120 days are considered as the time of generating emissions, due to crop and water management involved in rice production.

1.) Methane (CH_4) emissions to air

In this research, the calculation of CH_4 emissions from paddy rice fields followed the IPCC guidelines (2006), which propose a model for calculating daily emissions, based upon a baseline emission factor EFc (equation 4.4).

$$EF_i = EF_c \cdot SF_w \cdot SF_p \cdot SF_0 \cdot SF_{s,r} \qquad \text{(equation 4.4)}$$

Where:

EF_i = adjusted daily emission factor for a particular harvested area, kg-CH_4.ha^{-1}.d^{-1}

EF_c = baseline emission factor for continuously flooded fields without organic amendments

SF_w = scaling factor to account for the differences in water regime during the cultivation period

SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period

SF_0 = scaling factor should vary for both type and amount of organic amendment applied

$SF_{s,r}$ = scaling factor for soil type, rice cultivar, etc., if available

EFc refers to the following conditions in a given cropping situation:

- Non-flooded pre-season has been less than 180 days prior to rice cultivation (or field is replanted within less than 180 days after previous flooded cropping; such situation actually refers to double –or multiple- cropping conditions);
- Continuous flooding during rice cultivation;
- No organic fertilization or organic residue incorporation.

Baseline emission factor EFc

IPCC (2006) suggests a default average global EFc of 1.30 kg-CH_4.ha^{-1}.d^{-1} (from Yan et al., 2005), yet with error ranging between 0.8 and 2.2. It has been decided to adjust EFc to Thailand conditions, on account of high soil, air and water temperatures, and high solar radiations, as proven determining factors of increased CH_4 emissions. Following IPCC's methodology, Yan et al. (2003a) investigated results from direct field measurements in South, South-East and East Asia, and recommended region-specific emission factors EFc of 2.04 and 3.12 kg-CH_4.ha^{-1}.d^{-1} for North and Northeast of Thailand, respectively.

All scaling factors have been based upon values recommended by IPCC (2006) and match the practices observed in all cropping systems studied

Scaling factors related to water regime (SFw and SFp)

SFw takes account of differences in water regime during the cultivation period. IPCC (2006) suggests the following values, shown in Table 4.16

Table 4.16 CH_4 emission scaling factors for water regime during cultivation, SFw

Continuous flooding	Intermittent flooding (single aeration)	Intermittent flooding (multiple aeration)	Rainfed (regular)	Rainfed (drought-prone)
1	0.6	0.52	0.28	0.25

Source: IPCC (2006) Note: Rainfed conditions refer here to lowland rice that is cropped under flooding conditions, yet with no full control of water. Rainfall, and not controlled irrigation, provides ponding conditions to paddy fields. Upland rice is not considered in the study.

The two study areas (North and North East) are ascribed difference factors, and calculations were considered the two cropping seasons in both areas, i.e. wet and dry season. Specific conditions were considered. For instance, due to dry conditions, continuous flooding in dry season hardly occurs in North-East, while rainfed conditions may not provide continuous flooding even in the wet season (drought-prone area).

According to the discussion with farmers in the North of Thailand, SFw factor of 1 (continuous flooding) is applied during wet-season in both Rw and Iw systems, but 0.52 is applied into Id systems (intermittent flooding). On the other hand SFw of 0.52 is applied to all rice cropping systems in the Northeast region. The farmers in the North region said that in the wet season, there is more than enough rainfall and irrigation water to ensure continuous flooding. It is different in the Northeast where surface water and rainfall is often not enough for irrigation. Indeed, rainfall data from both regions show that Northern region benefits about twice more precipitation than Northeast.

SFp refers to differences in water regime before cultivation period. IPCC (2006) suggests the following values, shown in Table 4.17. In our cases, we decided to ascribe a SFp factor of 0.68 to Rw systems, since there is about 6-7 months fallow before any wet season cropping, hence a non-flooded pre-season of more than 180 days. Iw and Id systems are ascribed a SFp factor of 1 since it is assumed that irrigated cycles follow each other in wet and dry seasons. This is a completely valid assumption in the North, but it is arguable in Northeast, where not all Iw systems are followed by Id systems. This means that a number of Iw systems may have been ascribed a SFp factor of 0.68 (see section on cropping intensity in chapter 5).

Table 4.17 CH_4 emission scaling factors for water regime before cultivation (pre-season), SFp

Non-flooded pre-season > 180 days	**Non-flooded pre-season < 180 days**	**Flooded pre-season > 30 days**
0.68	**1**	**1.90**

Source: IPCC (2006). Short flooding periods (< 30 days) for land preparation are not considered.

In Nam Mae Lao basin, we considered the straw incorporation time (in the soil) greater than 30 days (before cropping) for all the systems because farmers perform the first land preparation for a new cycle within one or two days right after the previous harvest. For example, in irrigated system during the wet season (Iw), farmers harvest rice at the end of October and then start land preparation in the first week of November, while next rice cropping will actually start in the 2nd week of January. Therefore, the time of straw incorporation is greater than 30 days for Iw systems. The same principle applies to Id systems, where 1st time land preparation for next crop starts immediately after harvesting (first week of May), while next crop actually will be planted near the the end of June.. The same logic applies to Rw systems of N and NE. It is different in irrigated systems in Northeast; the 1st land preparation takes place when the growing period begins. Therefore the time of straw incorporations is less than 30 days for Iw and Id systems in the Northeast.

Scaling factor related to organic amendments

SFo is the scaling factor reflecting both type and amount of organic matter applied. Equation 4.5 determines SFo (IPCC, 2006).

$$SF_0 = \left(1 + \sum_i ROA_i \cdot CFOA_i\right)^{0.59} \qquad \text{(equation 4.5)}$$

Where:

SF_0 = scaling factor for both type and amount of organic amendment applied

ROA_i = application rate of organic amendment i, in dry weight of rice straw (as practiced in study areas, ton ha^{-1}

$CFOA_i$ = conversion factor for organic amendment i (in terms of its relative effect with respect to straw applied shortly before cultivation) (IPCC guideline, 2006)

With regards to common practices in the study areas, organic amendments include only rice straw that remains after harvesting. Literature commonly considers a dry grain / dry straw ratio of 1:1. Assuming that dry grain yield of previous crop matches the average yield attained at the regional level for both regions, it is suggested that dry straw weights 3.4 and 2.5 tons.ha^{-1} in North and North East respectively, and remains for incorporation as organic fertilizer. Such amounts from the base application rates ROA. Table 4.18 shows alternative values, in case straw is either burned or grazed in the field before incorporation, which scenarios occur on occasions in the study areas. For this research, it assumed that all straw remains non-burnt, non-grazed, and is incorporated, as it is the most common practice by far.

Table 4.18 Application rate of organic amendment ROA, according to in-field straw management (ton.ha^{-1})

Full incorporation in soil	Livestock grazing	In-field burning
North: 3.4 **North East: 2.7**	**0.5**	**0.3**

Source: authors' data and assumptions, on account of field observations. Note: in-field burning is never complete and leaves at least rice rooting systems.

The conversion factor for organic amendment CFOA refers to its relative effect with respect to application time, as shown in Table 4.19.

Table 4.19 Conversion factor for dry straw as organic amendment CFOA

Straw incorporated less than 30 days before cultivation	Straw incorporated more than 30 days before cultivation
1	**0.29**

Source: IPCC (2006)

Table 4.20 recaps the calculated EFi on account of most common situations in North and North East study areas, respectively. All the scaling factors were set depend on the observation of the samplings.

Table 4.20 The emissions factors and its scaling factor based on IPCC guideline (2006), and Yan et al. (2003) for North and Northeast of Thailand conditions

Factor effecting the emissions	Emission scaling factors of each condition			Emission scaling factors of each condition		
1.) Agroecological zone	Lam Sieo Yai basin (Northeast)			Nam Mae Lao (North)		
2.) Cropping Season	Wet season		Dry season	Wet season		Dry season
3.) Cropping System	Rainfed	Irrigated	Irrigated	Rainfed	Irrigated	Irrigated
Default baseline emission factor (kg-CH_4.ha^{-1}.d^{-1})	3.12	3.12	3.12	2.04	2.04	2.04
3.1) Water regime during the cultivation period	Intermittent flooding (multiple aeration)	Intermittent flooding (multiple aeration)	Intermittent flooding (multiple aeration)	Continuous flooding	Continuous flooding	Intermittent flooding (multiple aeration)
	0.52	0.52	0.52	1	1	0.52
3.2) Water regime before the cultivation period	Non flooded preseason > 180 d	Non flooded preseason < 180 d	Non flooded preseason < 180 d	Non flooded preseason > 180 d	Non flooded preseason < 180 d	Non flooded preseason < 180 d
	0.68	1	1	0.68	1	1
4.) organic amendments	Straw > 30 d	Straw < 30 d	Straw < 30 d	Straw > 30 d	Straw > 30 d	Straw > 30 d
4.1) Conversion factor	0.29	1	1	0.29	0.29	0.29
4.2) The application rate (ton ha^{-1})	2.5	2.5	2.5	3.4	3.4	3.4
4.3) Scaling factors for organic amendments	1.379	2.094	2.094	1.499	1.499	1.499
Adjusted Daily emission factor (kg CH_4 ha^{-1} d^{-1})	1.522	3.397	3.397	2.079	3.058	1.590

2.) N_2O emissions from rice cultivation to air

Because of flooded conditions, unfavorable to nitrification, N_2O and NOx emissions have long been assumed negligible in paddy rice production. Yan et al. (2003b) reviewed literature with measurements of N_2O emissions from paddy fields. Those included unfertilized plots in order to derive fertilizer-induced emissions. The model is specific to paddy rice, but not to Thailand or South East Asia. Also, the report is oriented towards assessment of total emissions from land use perspective, and considers emissions from the fallow land in between rice cropping, including background N_2O emissions. Owing to LCA, product-oriented approach in this study, it is chosen to focus on emissions occurring during the cropping cycle leading to the final product. From statistical analysis of 21 experimentations, Yan et al. (2003b) derived both an average fertilizer-induced emission factor (0.25% of all N fertilizing units applied), and an average baseline emission of 0.26 kg $N\text{-}N_2O.ha^{-1}$ for an average season of 117 days. Equation 4.6 captures that model, which, however fails to consider intermittent flooding conditions, with drying periods where more active nitrification-denitrification occurs, probably leading to higher N_2O emissions.

$$\mathrm{N - N_2O\ kg.ha^{-1}} = [0.0025 \cdot \mathrm{Nf}] + [0.26 \cdot \mathrm{D}/117] \qquad \text{(equation 4.6)}$$

Where:

Nf: Total N units applied through chemical fertilization, per ha, the during cropping cycle) which depending on the observation of the sampling
0.0025: Average fertilizer-induced emission factor (0.25%)
D: Actual duration of cropping season
0.26 N $kg.ha^{-1}$ Average baseline $N\text{-}N_2O$ emission over 117-day season

3.) NO emissions from rice cultivation to air

With a similar approach as the one used for N_2O emissions (yet with fewer experimental results), Yan et al. (2003b) investigated literature on NOx emissions. They came up with an average fertilizer-induced emission factor (0.13% of all N fertilizing units applied), and an average baseline emission of 0.57 kg $N\text{-}NO.ha^{-1}$ for an entire year. Equation 4.7 captures that model, which however fails to consider intermittent flooding conditions, with drying periods where more active nitrification-denitrification occurs, probably leading to higher NOx emissions.

$$\mathrm{N - NO\ kg.ha^{-1}} = [0.0013 \cdot \mathrm{Nf}] + [0.57 \cdot \mathrm{D}/365] \qquad \text{(equation 4.7)}$$

Where:

Nf: Total N units applied through chemical fertilization, per ha, during the cropping cycle) which depending on the observation of the sampling
0.0013: Average fertilizer-induced emission factor (0.13%)
D: Actual duration of cropping season
0.57 N $kg.ha^{-1}$ Average baseline N-NO emission over 365 days

4.) NH_3 emissions from rice cultivation to air (volatilization)

According to FAO stats (2002) and in agreement with field data collected in the study areas in 2010-2011, urea and ammonium-based fertilizers from about 85% of all nitrogen fertilizers applied to paddy fields in North and North East Thailand.

Yan et al. (2003b) focused literature analysis of urea-induced NH_3 emissions since urea is the most common chemical fertilizer used by farmers in South and South East Asia. Timing and mode of application have a strong influence on volatilization rate. As proposed by Yan et al. (2003b), urea-induced NH_3 emissions depend upon timing and mode of application, as follows: volatilization forms 20% of application when incorporation is performed in land preparation, 36% when urea is top-dressed (broadcast) after transplantation / seedling, 12% when application occurs at the time of panicle initiation. Urea-induced emissions follow the model shown in equation 4.8. Considering the distribution of urea application as 30%, 30%, 40% at land preparation, after plantation, and at panicle initiation respectively, an average urea-induced emission factor may be calculated as 22%.

$N\text{-}NH_3$ $kg.ha^{-1}$ from urea =
$(U_{inc} * 0.46 * 0.2) + (U_{trans} * 0.46 * 0.36) + (U_{pa}n * 0.46 * 0.12)$ (equation 4.8)

Where:
0.46: conversion factor from N-Urea to Urea
Ui_{nc} : Mass of urea applied and incorporated in soil at land preparation time
U_{trans} : Mass of urea broadcast (top-dressed) after transplantation / seedling time, during the vegetative phase
U_{pan} : Mass of urea broadcast (top-dressed) around the panicle initiation stage

All the mass of urea application are depended on the sampling.

Paucity of experiments and measurements did not allow for detailed emission factors for other fertilizers. Yan et al. (2003b), partially using EEA guidelines, recommend the following average NH_3 emission factors for the nitrogen-based fertilizers: ammonium bicarbonate (33%), ammonium sulfate (22%), ammonium phosphate (5%), all other nitrogen-based or multiple-nutrient (N-P-K) fertilizers (2%). They also recommend a background emission of 1.5 kg $N\text{-}NH_3.ha^{-1}.yr^{-1}$.

Therefore, total NH_3 emissions to air from paddy fields may be modeled and calculated as follows:

$N\text{-}NH_3$ $kg.ha^{-1}$ =
[$N\text{-}NH_3$ $kg.ha^{-1}$ from urea] + (N-AB * 0.33) + (N-AS * 0.22) + (N-AP * 0.05) +
(N-Others * 0.02) + (1.5 kg $N\text{-}NH_3.ha^{-1}.yr^{-1}$ * D/365) (equation 4.9)

Where:
$N\text{-}NH_3$ $kg.ha^{-1}$: N units from urea (see equation 5.5)
N-AB : N units from ammonium bicarbonate ($kg.ha^{-1}$)
N-AS : N units from ammonium sulfate ($kg.ha^{-1}$)
N-AP : N units from ammonium phosphate ($kg.ha^{-1}$)
N-Others : N units from all other nitrogen-based fertilizers and multiple-nutrient formulas ($kg.ha^{-1}$)
D: Actual cropping cycle duration
(1.5 kg $N\text{-}NH_3.ha^{-1}.yr^{-1}$ * D/365): background emission, adjusted to D

5.) Nitrates emissions from rice cultivation to water

While nitrogen is the core of fertilization in paddy rice cropping, the crop consumes significantly more ammonium forms than nitrates, conversely to other global crops. Also, owing to flooded conditions, fertilization is rather ammonium and urea-oriented since soluble nitrates may easily leach. As said earlier, according to FAO stats (2002) and in agreement with field data collected in the study areas in 2010-2011, urea and ammonium-based fertilizers from about 85% of all nitrogen fertilizers applied to paddy fields in North and North East Thailand. Therefore, direct nitrates emissions result mostly from complex biochemical transformations (e.g. denitrification) and the whole nitrogen cycle and balance, rather than direct fertilizer loss.

The principles underlying nitrate emission assessment is that (1) nitrates form the remaining components of the overall nitrogen mass balance, which other components have been determined in earlier sections, (2) a large portion (majority) of these nitrates may leach to water compartment, through surface drainage and deep percolation, and (3) such portion refers to the ratio between water that is not used by the crop and overall water supply; in other terms, it relates to water use efficiency.

Accordingly, nitrates potentially leaching from a paddy field are modeled according to a dual N and water mass balance approach suggested by Pathak et al. (2004). N inputs include fertilizer, precipitation, irrigation water and soils (N stock, immobilization). N outputs include losses in surface runoff, groundwater, harvested and exported crop components (rice ears mostly), soil losses (erosion), mineralization, volatilization, denitrification processes.

Nitrogen mass balance

The nitrogen mass balance can be expressed as:

$$0= N_{in} - N_{out} - N_{diff\,soil} \qquad \text{(equation 4.10)}$$

The components of N_{in} (inputs) and N_{out} (outputs) are shown in Table 4.21. N_{diff} soil is the difference in N stored in pre-cultivation soil and N stored in post-cultivation soil. Under same cropping systems for years, these soils have long-term stable nitrogen contents, therefore N_{diff} soil is deemed negligible. Similarly, organic matter dynamic is deemed balanced overtime, with equal mineralization and immobilization. Other component such as biological nitrogen fixation (-), groundwater contribution (+), and exports by weeds (-) are ignored (Pathak et al., 2004).

Table 4.21 Components of nitrogen balance in paddy fields

N input (kg N ha^{-1})	**N output (kg N ha^{-1})**
+ N fertilizer + N from precipitation + N from irrigation water + N from mineralization of organic matter	- N net export by crops - N loss due to emissions of N_2O, NO and NH_3 - N loss due to N_2 emissions - N loss in deep percolation - N loss in drained water - N loss by immobilization in organic matter
∑ input	**∑ output**
N balance = 0 = ∑ input - ∑ output – $N_{diff\,soil}$	

All components of Table 4.21 are known, assumed or neglected, except for N losses in deep percolation and surface drainage. These are highly water-soluble nitrates, which may be leaching to the water compartment.

N inputs from fertilizer are to be calculated from fertilizers' formulas and application doses. N inputs from rainfall and irrigation water are to be calculated from data on N contents, average precipitation and irrigation data over the period under consideration (cropping cycle). They may be neglected in the absence of data on N content in rainfall or irrigation.

N uptake by rice plants (mostly ears) are to be calculated from the average mass of exported parts (grain and ears) and their average N contents. If rice straw is also exported off the field, grazed or burned, its N content should also be considered lost.

N loss due to emissions of N_2O, NO and NH_3 can be calculated according to section 4.3.2, 4.3.3 and 4.3.4.

N_2 is emitted during the last phases of denitrification. Although not a pollutant, N_2 needs are assessed in order to complete the whole mass balance. Brentrup et al. (2000) proposes an emission factor linked to overall N fertilization:

$$N\text{-}N_2\ (kg/ha) = (0.09 * \text{Total N units per ha}) \qquad \text{(equation 4.11)}$$

It is assumed that the remaining components are most nitrates (Nt), which result from nitrification of ammonia. If not absorbed by the crop through evapotranspiration flux, they will potentially be emitted to the water compartment as pollutants, via deep percolation and drainage (Nl).

As indicated in Table 4.21, they form losses through surface drainage and deep percolation.

<u>Water balance</u>

A water mass balance is needed to ascertain the water use efficiency ratio Ei. It is assumed that the proportion of nitrates bound to drain or leach to the surface and ground water compartments (Leachable nitrates; Nl) during the crop cycle equals the proportion of water that is unused by crops in the paddy system : [1 - Ei].

$$Nl = Nt * [1 - Ei] \qquad \text{(equation 4.12)}$$

The water balance equation may be expressed as follows, in order to determine percolation and drainage components:

$$DPR + R = I + P - ET \qquad \text{(equation 4.13)}$$

Where:

DPR = Deep water percolation in mm

R = Runoff from the paddy field, which can be expressed as the surface drainage, in mm

I = Irrigation water applied during the day in mm

P = Precipitation in mm

ET = Evapotranspiration in mm

Note: runoff itself is considered nil, since in common conditions, paddy fields are flat and managed in a way that prevents water from spilling over bunds; farmers maintain water depth between defined minimal and maximal ponding conditions (0 to 150 mm generally). However, at times, and especially at the end of the cropping season, near harvesting, farmers drain the fields off.

Typically, irrigation efficiency, or water use efficiency ratio is:

$$Ei = ET / [P + I] \qquad \text{(equation 4.14)}$$

It may also be expressed as a function of DPR and R, as follows:

$$1 - Ei = [DRP + R] / [P + I] \qquad \text{(equation 4.15)}$$

Either ways, one requires running a water balance model in order to calculate the proportion of nitrates bound to drain or leach to the surface and ground water compartments (Nl). Equation 4.15 conveniently requires less components to be determined. Average monthly rainfall data, and ET data provided by meteorological services may be used, as well as typical irrigation data collected in the study area. However, more detailed analysis with a dedicated model such as CropWat (FAO, 1992) provides more accurate results.

<u>Calculation example: a rice cropping scenario in Northeast of Thailand (Lam Sieo Yai Basin), rainfed rice, wet season.</u>

The model and calculations were tested under normal paddy field condition in the Northeast of Thailand (Lam Sieo Yai Basin). A paddy field under rainfed condition is taken as an example. The actual duration of cropping season is D = 125 days between July-October.

N Input parameters

<u>N from fertilization:</u>

Fertilization plan (typical of rainfed paddy rice in North East Thailand):

- In early rice season (after transplanting or sowing), 100 kg.ha^{-1} urea (46-0-0)
  That is 100 kg.ha^{-1} * 0.46 = 46 kg-N units.ha^{-1}
- In the mid season, 125 kg.ha^{-1} Ammonium Phosphate (16-20-0)
  That is 125 kg.ha^{-1} * 0.16 = 20 kg-N units.ha^{-1}
- 1 month before harvesting (panicle initiation) 300kg composite fertilizer (15-15-15)
  That is 300 kg.ha^{-1} * 0.15 = 45 kg-N units.ha-1

Total application rate of N equal to 46 + 20 + 45 = 111 kg-N ha^{-1}

D: 125

<u>N from precipitation:</u>

Sources from the Pollution Control Department of Thailand allowed determining certain input data, as follows (average values):

- NO_3 concentration in precipitation: 0.7 mg.l^{-1}

1 mm of rainfall represents 1 liter per square meter, or 10,000 liter per ha.
So, 1 mm of rainfall over 1 ha brings;

$$= 10{,}000 \ \mathrm{l} \times 0.7 \frac{\mathrm{mg}}{\mathrm{l}} = 7000 \,\mathrm{mg} = 0.007 \,\mathrm{kg} \text{ nitrates}$$

Rainfall data of the last 30 years (1980-2010) were collected from Thailand Meteorological Department rainfall stations located in the study area; average monthly precipitations feature in Table 4.22.

Table 4.22 Average 30 years monthly rainfall (mm) in Lam Sieo Yai Basin

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Monthly rainfall (mm)	10	2.3	18.5	16.4	80	43.4	142.1	202.9	259.7	103	5.4	2

The actual duration of cropping season is D = 125 days between July-October and the total rainfall are 142.1 + 202.9 + 259.7 + 103 = 707.7 mm. Therefore the amount of NO_3 input from precipitation is:

0.007 * 707.7 = 4.95 kg NO3.ha^{-1}
Or:
4.9539 * 14/62 = 1.12 kg N-NO_3.ha^{-1}

N from irrigation:
For example, the average of NO_3 concentration in irrigated water in Thailand is 0.11 mg.l^{-1}, therefore 1 mm irrigation brings 11 g NO_3 per ha. More accurate water balance is performed here below. At that point, and considering the small nitrate contribution of irrigation water, one may take a typical irrigation amount (e.g. 10,000 m^3 for paddy rice). In the example, there is no irrigation water supply, so irrigation NO_3 contribution is nil.

Total N inputs: 111 + 1.12 = 112.12 kg N units. ha^{-1}

N Output parameters:
N net export by crops:

- Average total nitrogen concentrations in harvested grains which include rice grains and husk, stems, leaves and roots are 1.23, 0.51, 0.75 and 0.63 % of dry matter, respectively.
- The average yield is 2,500 kg.ha^{-1} (dry grain)
- Stems, leaves and roots remain in the field and contribute to N immobilization in organic matter (counterbalancing mineralization) (note that if burnt or grazed, stems and leaves must be then be included as net exports).

The total amount of nitrogen stored in harvested plant tissues is:
2,500 * 1.23/100 = **30.75** kg N units.ha^{-1}

N losses by direct emission of N_2O, NO_x, NH_3, N_2:
Emissions to air (from section 4.3.2 to 4.3.4)
N-N_2O kg.ha^{-1} = 0.56
N-NO kg.ha^{-1} = 0.34
Total N-NH_3 emissions to air (kg.ha^{-1}) = 18.97
N-N2 (kg/ha) = (0,09 * Total N units per ha) = 0.09 * 111 = 9.99

From the nitrogen balance presented here above, there is a calculated excess as follows:
Total inputs: 112.1186 kg N units. ha^{-1}
Total outputs: 30.75+0.56+0.34+18.97+9.99 = 60.61 kg N units. ha^{-1}
Excess: 112.12 - 60.61 = 51.51 kg N units.ha^{-1}

It is assumed that the remaining components (excess) are mostly nitrates, which result from nitrification of ammonia. If not absorbed by the crop through evapotranspiration flux, they will potentially be emitted to the groundwater and surface water compartments as pollutants, via deep percolation and drainage. Hence the need to determine the ratio [ET / DPR + R]. It is also assumed that nitrate concentration is the same in ET, DPR and R waters.

N loss in drained water:

N losses due to drained water (runoff and also drained water before harvesting) are also included in the model (as mentioned in Table 4.21). In this example of rice cropping under rainfed condition in the Northeast, there is no drained water during the growing season and before harvesting. Therefore, N losses due to drained water are nil.

N losses in deep percolation:

Deep percolation can be estimated by using equation 4.13 ($DPR + R = I + P - ET$).

According to this rainfed case study, there are no drainage water (R = 0); total rainfall is 707.7mm. Potential evapotranspiration or reference crop evapotranspiration (ETo) is estimated using the Penman-Monteith method as recommended by FAO (1992). Actual evapotranspiration (ET_a) is then calculated based on crop coefficient (K_c).

Table 4.23 gives the values of crop coefficients (K_c) for rice at different growth stage. CROPWAT, a model developed by the Food and Agriculture Organization of the United Nations (FAO) may be used to calculate ET_a. Soil data may be retrieved from the CROPWAT database.

Table 4.23 Crop coefficients of rice at growth stage

Crop coefficients (K_c)	**Growth Stage**				**References**
	Initial	Development	Mid-season	Ripening	
Wet season	1.05	1.43	1.63	1.15	FAO
Dry season	0.47	1.33	1.51	0.86	RID

The total ET_a is determined at **542.1 mm** in the example.

So, $DPR + 0 = 0 + 707.7 - 542.1 = 165.6$ mm

According to equation 4.11, water use efficiency Ei is:

Ei = 542.1 / 707.7 *100 = 76.6 %

According to equation 4.15,

$$1 - Ei = [DRP + R] / [P + I]$$
$$= [165.6 + 0] / [707.7 + 0]$$
$$= \mathbf{0.234}$$

So, $Nl = Nt * [1 - Ei]$

$$= 51.5101 * 0.234 * 62/14$$
$$= \mathbf{53.38\ kg\ NO_3.ha^{-1}}$$

62/14: conversion factor from N units to NO_3

Note that DPR = 165.6mm ; that makes 1,656,000 liters per ha. If containing 53.38 kg NO3, that makes a concentration of 0.03223g per liter, or 32.233 mg.l^{-1} in percolating waters, this falls within a realistic range. Measurements of nitrate concentration in groundwater near rice fields in various locations in Thailand fall within a range between 5 to 60 mg.l^{-1}, (Tirado, 2007); the WHO safety limit for drinking water is 50 mg. l^{-1}.

6.) Phosphorus emissions from rice cultivation to water

Phosphorus (P) is an input to the rice cropping system through chemical fertilizer application, rainwater and irrigation water. Outputs and losses occur through plant uptake and export, percolation and surface drainage which result in pollution (eutrophication). A phosphorus mass balance can be expressed as:

$$0 = P_{in} - P_{out} - P_{diff\,soil} \qquad \text{(equation 4.16)}$$

The components of P_{in} (inputs) and P_{out} (outputs) are shown in Table 4.24. $P_{diff\ soil}$ is the difference in P stored in pre-cultivation soil and P stored in the post-cultivation soil. Under same cropping systems for years, paddy soils have long-term stable phosphorus contents, therefore $P_{diff\ soil}$ is deemed negligible. Similarly, organic matter dynamic is deemed balanced overtime, with equal mineralization and immobilization. Paddy fields being flat and protected by bunds, water hardly ever spills over (except in case of exceptional flooding conditions). So, soil erosion by excessive runoff hardly exists and may be neglected as a possible source of P loss.

Table 4.24 Components of phosphorus balance in paddy fields

P input (kg N ha^{-1})	**P output (kg N ha^{-1})**
+ P fertilizer + P from precipitation + P from irrigation water + P from immobilization (=mineralization of organic matter)	- P uptake by plants - P loss in deep percolation - P loss in drained water - P loss to mineralization of organic matter (=immobilization)
∑ input	**∑ output**
P balance = 0 = ∑ input - ∑ output – $P_{diff\ soil}$	

P inputs from fertilizer are to be calculated from fertilizers' formulas and application doses.

P inputs from rainfall and irrigation water are to be calculated from data on P contents, average precipitation and irrigation data over the period under consideration (cropping cycle). They may be neglected in the absence of data on P content in rainfall or irrigation.

P uptake by rice plants (mostly ears) are to be calculated from the average mass of exported parts (grain and ears) and their average P contents. If rice straw is also exported off the field or grazed, its P content should also be considered lost. If burning occurs in the field, P is supposed to stay there.

A water mass balance is needed to calculate the total phosphorus losses due to drainage and leaching to surface and groundwater compartments respectively (Pl). The same approach as the one used for nitrates (section 4.3.5) is used here. It is assumed that the proportion of phosphorus (phosphates) bound to drain or leach to the surface and ground water compartments (Leachable phosphorus; Pl) during the crop cycle equals the proportion of water that is unused by crops in the paddy system : [1 - Ei].

$$Pl = Pt * [1 - Ei] \qquad \text{(equation 4.17)}$$

Equations 4.13 to 4.15 will be used again, leading to an estimation of phosphorus losses (emissions) to water (see section 4.3.5 for details).

Calculation example: a rice cropping scenario in Northeast of Thailand (Lam Sieo Yai Basin), rainfed rice, wet season.

The model and calculations were tested under normal paddy field condition in the Northeast of Thailand (Lam Sieo Yai Basin). A paddy field under rainfed condition is taken as an example. The actual duration of cropping season is D = 125 days between July-October.

P Input parameters

P from fertilization:

- During the vegetative phase (mid season), 125 $kg.ha^{-1}$ Ammonium phosphate (16-20-0) That is 125 $kg.ha^{-1}$ * 0.20 = 25 kg P $units.ha^{-1}$
- 1 month before harvesting, 300 kg ha^{-1} composite fertilizer (15-15-15) That is 300 kg ha^{-1} * 0.15 = 45 kg P $units.ha^{-1}$

Total application (inputs) of P equal to 25 + 45 = **70 kg** P-$units.ha^{-1}$

P from precipitation:

The Pollution Control Department of Thailand provides an average value for P concentration in precipitation in Thailand: 0.045 $mg.l^{-1}$

So, 1 mm of rainfall in 1 ha brings:

$$10{,}000 \ \mathrm{l} \times 0.045 \frac{\mathrm{mg}}{\mathrm{l}} = 450 \, \mathrm{mg} = 0.00045 \, \mathrm{kg}$$

From Table 4.22, rainfall over the cropping season amounts to 707.7 mm during July-October (125 days). Therefore the amount of P from precipitation is:

0.00045 * 707.7 = **0.318 kg** P-$units.ha^{-1}$

P from irrigation:

The same method applies. For example, the average P concentration in irrigation water in Thailand is 0.125 $mg.l^{-1}$, therefore 1mm irrigation brings 1.25 g P-units per ha. More accurate water balance will be performed later. At that point, and considering the small contribution of irrigation water, one may take a typical irrigation amount (e.g. 10000m^3 for paddy). In the example, there is no irrigation water supply, so irrigation P contribution is nil.

P Output parameters:

P uptake by plants:

- Average P concentrations in harvested grains, stems, leaves and roots were 0.5, 0.2, 0.3 and 0.3 % of dry matter, respectively.
- The average yield is 2,500 kg.ha^{-1} (dry grain)
- Stems, leaves and roots remain in the field and contribute to P immobilization in organic matter (counterbalancing mineralization) (note that if exported or grazed, stems and leaves must be then be included as net exports).

The total amount of P stored in harvested plant tissues (dry grain) is
2,500 * 0.5/100 = **12.5 kg** P-units.ha^{-1}

Total inputs = 70 + 0.318 = **70.318 kg** P-Units.ha^{-1}
Total outputs = **12.5 kg** P-units.ha^{-1}
Excess or Pt: 70.318 - 12.5 = **57.818** kg P-units. ha^{-1}

It is assumed that the remaining phosphorus components (excess or Pt) are mostly phosphate salts. If not absorbed by the crop through evapotranspiration flux, they will potentially be emitted to the groundwater and surface water compartments as pollutants, via deep percolation and drainage; hence the need to determine the ratio [ET / DPR + R]. It is also assumed that phosphate concentration is the same in ET, DPR and R waters.

P loss in drained water:
P losses due to drained water (runoff and also drained water before harvesting) are also included in the model (as mentioned in Table 4.24). In the case study, a rice cropping system under rainfed condition in the Northeast, there is no drained water during the growing season and before harvesting. Therefore, P losses due to drained water are nil.

P losses in deep percolation:
P losses due to deep percolation can be determined by equation 4.16 (Pl = Pt * [1 - Ei]).

Where:
Pt = **52.818** kg P-units. ha^{-1} (total phosphorus in excess, potentially leachable to ground and surface waters)
From the previous section: [1 – Ei] = 0.234.
Therefore, Pl = Pt * [1 - Ei]
= 52.818 * 0.234 = **12.35 kg** P-units.ha^{-1}

That makes 95/31 * 12.35 = **37.8 kg** P-PO_4 per ha (phosphates)

95/31: conversion ratio from P to P-PO_4

Note that DPR = 165.6mm ; that makes 1,656,000 liters per ha. If containing 37.8 kg P-PO_4 per ha, that makes a concentration of 22.9 mg.l^{-1} in percolating waters. The WHO safety limit for drinking water is 5mg. l^{-1}.

7.) Pesticides emissions from rice cultivation to water and soil

It is assumed that 100% of pesticides ultimately end up in both soil and water compartments, since none is supposed to concentrate in rice grain and leave the field at harvest. Most cropping systems indeed leave straw and rooting systems in the field to decay. In the production areas, most pesticides used are actually insecticides, which are hand-sprayed over the crop at different stages while the field is flooded most of the time.

Under the circumstances, it is arbitrarily decided to split emissions equally between soil and water compartments (50%-50%).

4.5.10 Computing indicators; LCIA

This task can be called “impact assessment phase”. It mostly involves computing of indicators from datasets which provided by field work and data collection.

LCIA: Potential environmental impact indicators

The environmental impacts were performed with SimaPro platform. FU-based impact indicators were calculated based on EcoInvent method and database. Midpoints indicators which including input-related indicators (energy use, abiotic resource depletion, biotic resource depletion) and output- related indicators (euthophication, acidification, global warming potential, ecotoxicity, ozone depletion) were assessed in this task.

4.5.11 Interpretation phase

Analysis of the results or interpretation phase; it is final step in LCA approach. This task consists of two main activities which are data analysis and interpretation of results.

Interpretation of results

In answers from this sector should be addressed the research question which mentioned in Chapter 1 and also including the investigation of the relationship between techno-economic performances, resource use and potential environmental impact and the optimization; maximize net income or yield, minimize production cost and environmental impacts.

4.6 Assessing technical and environmental efficiencies

To investigate the relationship between techno-economic performances, resource use and potential environmental impact, and optimization, Data Envelopment Analysis (DEA) concept was selected and MaxDEA Pro 6 (data envelopment analysis software; Gang & Zhenhua, 2005) was used as a tool to analyze all the efficiency results.

4.6.1 Data Envelopment Analysis (DEA)

As mentioned in Chapter 2, DEA is an established and well known methodology for nonparametric estimating the relative efficiency of a number of homogeneous units, commonly designated as Decision Making Units (DMU) (Cooper et al., 2000, 2004; Zhu, 2002). The efficiency score in the presence of multiple input and output factors is defined as:

$$\text{Efficiency score} = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}} \qquad \text{(equation 4.18)}$$

From the previous equation, it can be re-written into the equation below.

$$\text{Efficiency score} = \frac{a_1 y_{1i} + a_2 y_{2i} + \ldots + a_n y_{ni}}{b_1 x_{1i} + b_2 x_{2i} + \ldots + b_m x_{mi}} = \frac{\sum_{k=1}^{n} a_k y_{ki}}{\sum_{j=1}^{m} b_j x_{ji}} \qquad \text{(equation 4.19)}$$

Where 'x' and 'y' are the inputs and outputs of a DMU and 'a' and 'b' are the weights of inputs and outputs respectively, and 'k' and 'j' are the number of outputs and inputs produced by a DMU_i.

Three alternative approaches are available in DEA to estimate the efficient frontier as explained below.

- **Input-oriented**: the inputs are minimized and the outputs are kept at their current levels
- **Output-oriented**: maximized the outputs while maintaining the level of inputs
- **Mixed approaches**: minimized or increasing inputs while maximized or reducing the outputs.

Regarding to agricultural product, farmers can controls on the amount of inputs that they apply; therefore, *the input-oriented efficiency model* was selected in this research.

The **technical efficiency** is the minimum input bundle to produce a certain amount of outputs and **environmental efficiency** represents minimum environmental impacts to produce an amount of output.

MaxDEA Pro 6 (data envelopment analysis software; Gang & Zhenhua, 2005) was used as a tool to analyze all the efficiency.

CRS and VRS frontiers

The envelopment surface will differ depending on the scale assumptions that underpin the model. Two scale assumptions are generally employed: constant return to scale (CRS), and variable return to scale (VRS). The latter encompasses both increasing and decreasing returns to scale. CRS reflects the fact that output will change by the same proportion as inputs are changed (e.g. a doubling of all inputs will double output); VRS reflects the fact that production technology may exhibit increasing, constant and decreasing returns to scale. The effect of the scale assumption is demonstrated in Figure 4.4. Four data points (A, B, C, and D) are used to estimate the efficient frontier and the level of efficiency under both scale assumptions. With constant returns to scale, the frontier is defined by point C for all points along the frontier which indicates that both inputs can be proportionally reduced without reducing the amount of output, with all other points falling below the frontier (hence indicating inefficient). With variable returns to scale, the frontier is defined by points A, C and D, and only point B lies below the frontier i.e. exhibits inefficiency.

Input-oriented Constant Returns to Scale (CRS)

The equation 4.19 can be converted into a linear program to calculate the efficiency of i farm. Cooper et al. (2007) proposed that the efficiency was calculated by using the following DEA model:

$$Maximize\ \theta$$

Subject to

$$\theta x_0 - X\lambda \geq 0 \qquad (equation\ 4.20)$$

$$Y\lambda \geq y_0$$

$$\lambda \geq 0$$

Where;

θ is a scalar and its value obtained is the efficiency value of i farm.

λ is an intensity vector of weights of efficient DMU_i which helps to improve of inefficient DMU_i to the efficient frontier.

X and Y are inputs and outputs matrix of N number of farms, respectively.

x is the input vector of i farm and $_y$ represents net income of farm.

Input-oriented Variable Returns to Scale (VRS)

VRS developed by Banker et al. (1984) was calculated by using equation 4.21 as shown below.

$$Maximize\ z = uy_0 - u_0$$

Subject to

$$vx_0 = 1 \qquad (equation\ 4.21)$$

$$-vX + uY - u_0e \leq 0$$

$$u \geq 0, v \geq 0, and\ u_0\ free\ in\ sign$$

Where;

z is a scalar and is the efficiency of i farm and free in sign.

v is an input weight matrix.

u is an output weight matrix.

X and Y are inputs and outputs matrix of N number of farms, respectively.

If we replace $\lambda \geq 0$with $\lambda \leq 1$, then we obtain non-increasing return to scale (NIRS) model and if we replace $\lambda \geq 0$with $\lambda \geq 1$, non-decreasing return to scale (NDRS) model. If the efficient score from CRS = VRS = NIRS, it means DMU is the constant return to scale. If efficient score from CRS < 1 and CRS = NIRS, then DMU is increasing returns to scale, on the other hand, if efficient score from CRS < 1 and CRS < NIRS, the DMU is decreasing return to scale.

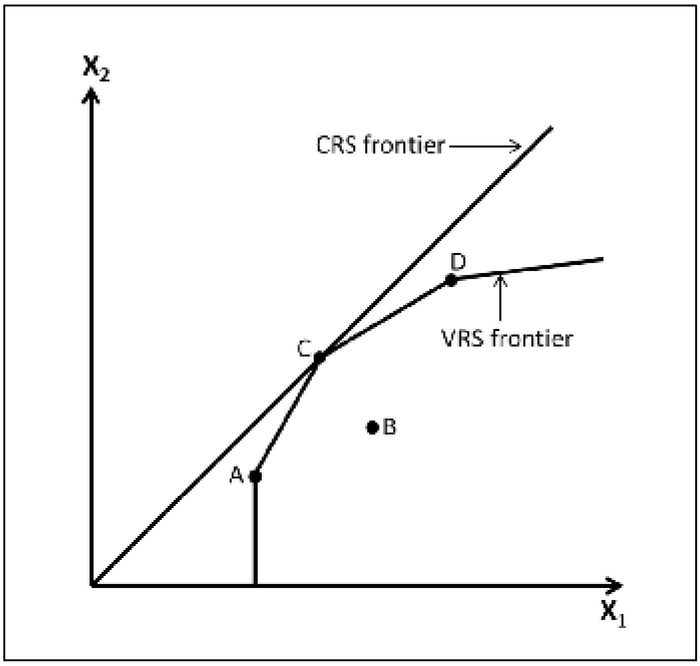
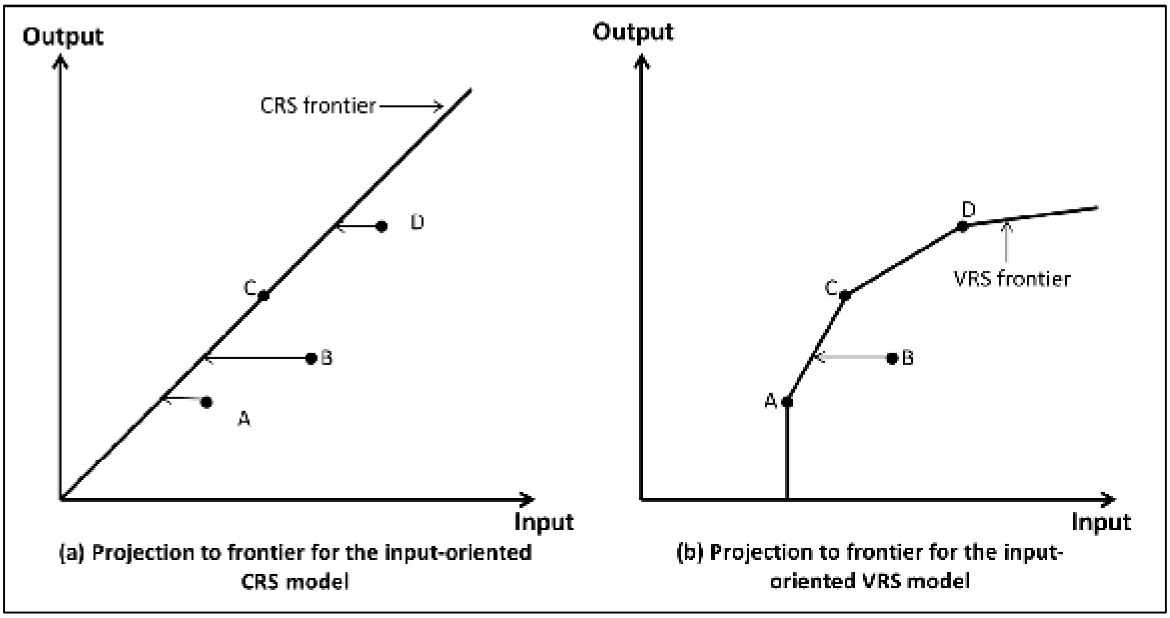


Figure 4.4 CRS and VRS frontiers

The efficiency frontier and DEA projections for input-oriented models are provided in Figure 4.5. For both cases (CRS and VRS models), C is on the frontier, it does not need reducing inputs. Only B lies below the frontier defined by VRS model, it means the set of inputs for B should be reduced. According to CRS, A, B and D should reduce inputs to achieve efficiency.



(a) Projection to frontier for the input-oriented CRS model

(b) Projection to frontier for the input-oriented VRS model

Figure 4.5 Projection to frontier for the input-oriented model

This study also includes the calculation Scale efficiency (SC) which can be calculated by the ratio of efficiency score of CRS and efficiency score of VRS. Scale efficiency helps to measure the efficiency due to the farming systems and it helps to measure the extent to which the farmers are using the optimal input mix to get a certain level of output. The SC is an indication of increasing return scale or decreasing return to scale.

4.6.2 Data sources and their indicators

In the case of paddy rice cropping in Thailand, the conventional DEA application requires some adaptations. The DMUs are cropping systems. While the yield is the undisputed output, dealing with inputs require some more caution since DMUs are essentially heterogeneous in the sense that there exist a diversity of practices, agrochemicals, machinery types and uses, water management ways and the like, most of which differ between DMUs, not only in quantity used but also in the occurrence. For instance, certain agrochemicals (fertilizers or pesticides) are interchangeable, used by some farmers and not by others. Also, their respective quantities for an expected result may differ, owing to different active ingredients' type or concentration for instance.

The choice was made to regroup inputs into three main clusters (fertilizers, pesticides, machinery) and to convert all into a monetary value equivalent (or production costs), baht as a single common unit. Technical efficiencies are computed based upon this combination of three production costs (resulting from inputs' use) against net income (outputs), for each cropping system (DMU).

Similarly, the same inputs' use in agricultural production may be translated into environmental impacts. LCA essentially consists of translating a diversity of inputs used in different quantities in each DMU (revealed during the inventory phase) into environmental impacts, with impact indicators with one single, common unit per impact category (e.g. gPO_4-eq. for Eutrophication Potential). Environmental efficiencies are computed based upon this combination of environmental impacts (resulting from inputs' use) against yields (outputs) for each DMU which can be shown in Table 4.25. Table 4.25 presents the different variables that were used as the inputs, their units, and methodologies or sources for the calculations.

Table 4.25 Variable of inputs, units, and method or sources used for calculation of technical and environmental efficiencies

Technical efficiency		
Variables of the inputs	**Units per ha**	**Method, source for calculation**
Cost of fertilizer	Baht	primary data (field survey)
Cost of pesticides		
Cost of Machinery		
Variables of the outputs	**Units per ha**	**Method, source for calculation**
Net income	Baht	primary data (field survey)
Environmental efficiency		
Variables of the inputs	**Units per ha**	**Method, source for calculation**
GWP_{100}	kg CO_2-eq	Primary data and LCA approaches
EP	kg PO_4-eq	
AP	kg SO_2-eq	
FAETP	kg 1,4-DB eq	
Water deprivation potential (WDP)	m^3 eq	water balance in paddy field model and the calculation of WSI
Mechanical or fossil energy (FEU)	MJ eq	primary data, conversion stands and LCA approach
Variables of the outputs	**Units per ha**	**Method, source for calculation**
Yield	kg	primary data (field survey)

We applied DEA to data collected in both basins. The envelopes are calculated across all 3 types (Id, Rw and Iw), meaning that DEA was applied to 60 samples per basin. Three methods (CRS, VRS and SC) are applied across all 3 types.

CHAPTER 5

DESCRIPTION OF HOM MALI RICE CROPPING SYSTEMS

This chapter includes identification and description of diverse typical Hom Mali rice cropping systems, including cropping calendar and cropping intensity in selected basins.

5.1 Hom Mali rice cropping systems

Both the Lam Sieo Yai and Nam Mae Lao basins are typical Hom Mali rice cropping basins, with different rainfed and irrigated cropping systems . In each system, there are three main methods to plant Hom Mali rice, i.e. direct sowing of dry seeds, direct sowing of wet (pre-soaked) seeds and traditional transplanting of seedlings (from nursery). Table 5.1 shows the percentage of farms using these different planting modes. As shown in Table 5.1, farmers practicing rainfed rice cropping prefer direct seeding of dry seeds, and that in both regions. In the North, irrigation farmers favor direct seeding of wet (pre-soaked) seeds, while in the Northeast, irrigation farmers prefer direct seeding of wet seeds. Sampling had to reflect this diversity as well. Figure 5.1 and Figure 5.2 show the growing rice by the broadcasting of dry and wet seeded and transplanting methods, respectively.

With different methods mean different input uses and sometimes show different output (yield). Based on primary data (samplings), the average yield can be shown in Table 5.2. According to this table both in north and northeast shows that the transplanting methods give the highest yield followed by sowing by wet seeded and dry seeded methods, respectively. Refer to the average yield from this table, 3,487 and 2,763 kg/ha are the average yields from Nam Mae Lao and Lam Sieo Yai basin, respectively which are not much different when compare with the secondary data 3,319 and 2,219 kg/ha (Table 5.3). The average yield of Thailand rice production (year 2011) is 2,281 kg/ha. The average yield from secondary data shows that yield in North is higher than the average yield of Thailand rice and average yield in the Northeast is lower. On the other hand, the average yield from the primary data shows that both yield from North and Northeast are higher than the average yield of the overall country.

Table 5.1 Methods to plant rice: statistics in Nam Mae Lao and Lam Sieo Yai basins

Method to plant Hom Mali rice	Percentage of the farmers			
	Nam Mae Lao basin (N)		Lam Sieo Yai basin (NE)	
	Irrigated (wet&dry)	Rainfed	Irrigated (wet&dry)	Rainfed
Dry seeds	20.0	81.3	75.4	75.0
Wet seeds	72.5	3.5	13.7	12.6
Transplanting	7.5	15.2	10.9	12.4
Total	100	100	100	100

Source: RID and MoAC

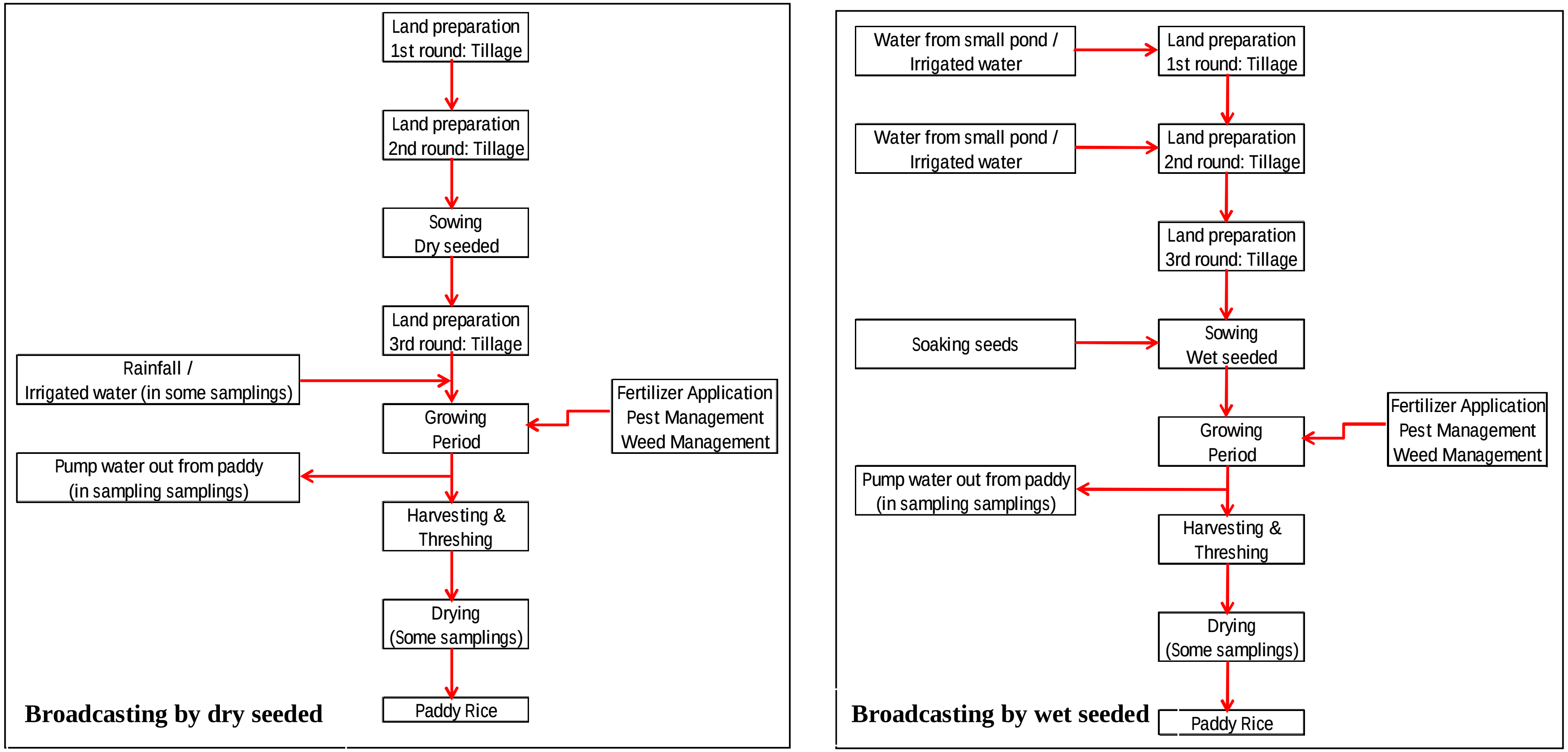


Figure 5.1 Planting rice by broadcasting of dry seeded and wet seeded methods

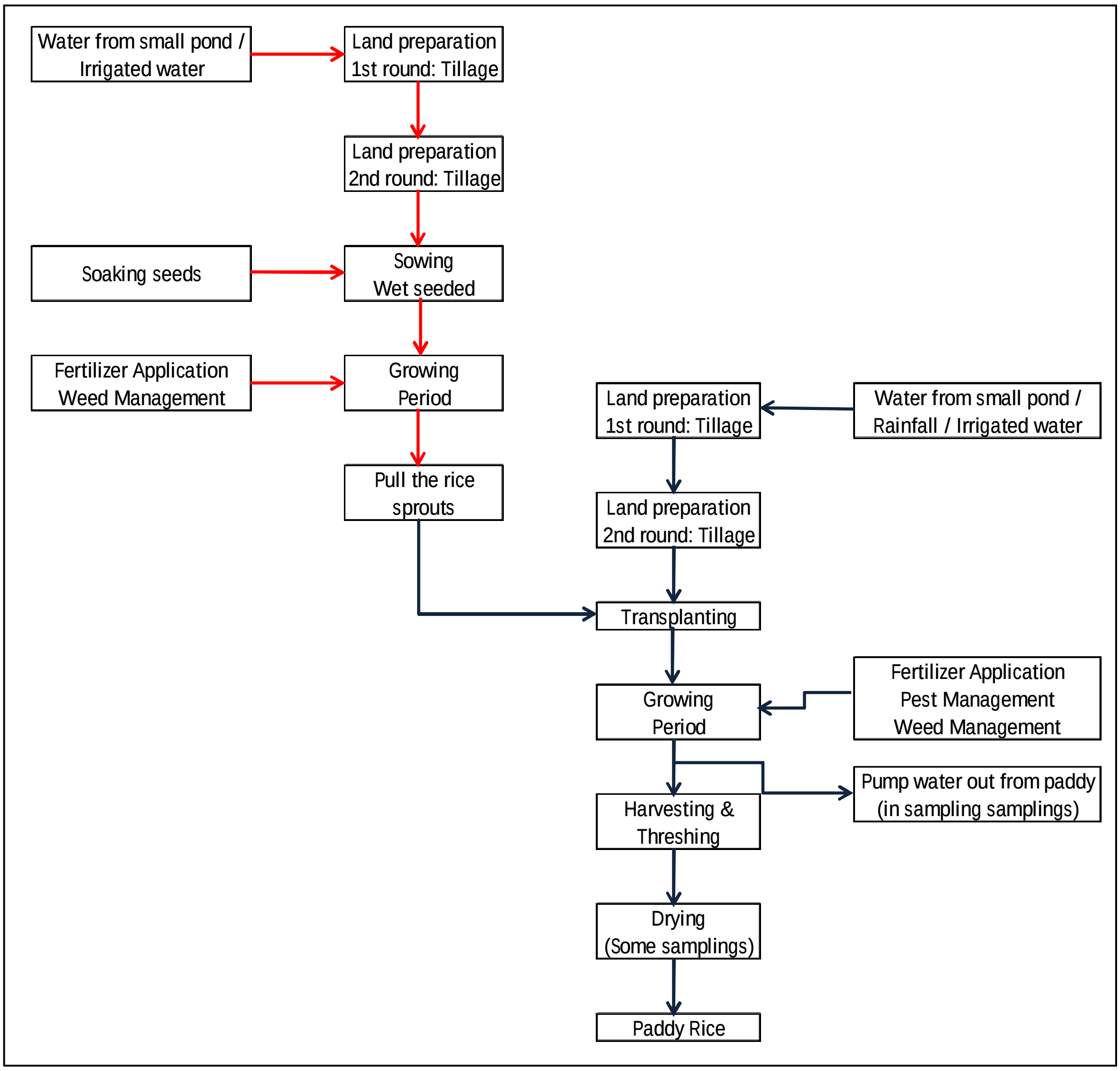


Figure 5.2 Planting rice by transplanting method

Table 5.2 Average yields from the samplings (kg/ha)

Method to grow Hom Mali rice	**Nam Mae Lao Basin (N)**			**Lam Sieo Yai Basin (NE)**		
	Irrigated		**Rainfed**	**Irrigated**		**Rainfed**
	Dry Season	**Wet Season**	**Wet Season**	**Dry Season**	**Wet Season**	**Wet Season**
Sowing dry seeds	3,275	3,438	3,125	2,219	2,656	2,363
Sowing wet seeds	3,406	3,656	3,463	2,625	3,000	2,813
Transplanting	3,563	3,813	3,644	2,988	3,188	3,019
average	**3,487**			**2,763**		

Table 5.3 Yields from secondary data (2010)

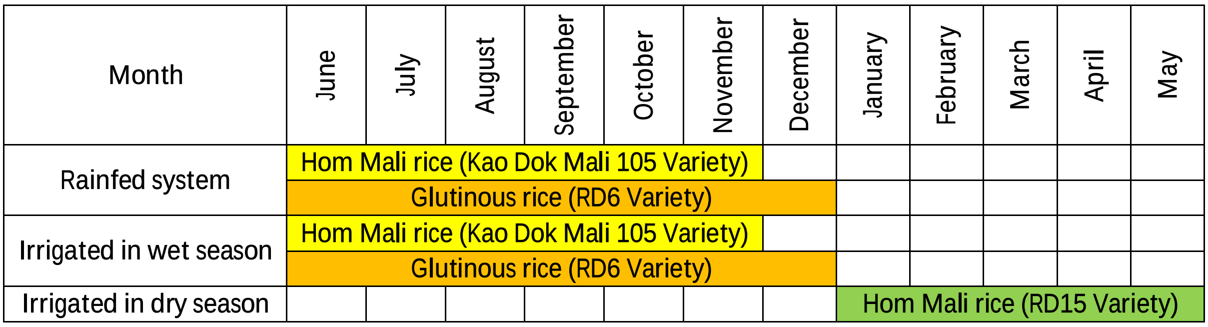
Locations	Yield of Hom mali rice (kg/ha)	Productions (ton)	%	Source
Thailand	2,281	6,613,794	-	MoAC
North of Thailand	3,238	1,015,828	15.36	
Northeast of Thailand	2,125	5,175,841	78.26	
Nam Mae lao basin	3,319	93,500	-	RID
Lam Sieo Yai Basin	2,219	498,800	-	

5.2 Cropping calendar of the paddy field in selected basins

This study was described based on the primary data (60 samplings in Nam Mae Lao and 60 samplings in Lam Sieo Yai basins) which was considered only the paddy field area. All cropping calendars in this section were referred to in the way of average or median from these samplings.

5.2.1 Cropping calendar of the paddy field in Nam Mae Lao Basin (North of Thailand)

Figure 5.3 shows the cropping calendar in the paddy field of Nam Mae Lao Basin. In wet season both in rainfed and irrigated system, there are two main varieties of rice were grown (Kao Dok Mali 105 and RD6 Varieties) and in the dry season with limited of time and water, farmers normally grows Hom Mali rice with RD15 variety. These three varieties are normally used in this study area.



<table>
<tr><th>Month</th><th>June</th><th>July</th><th>August</th><th>September</th><th>October</th><th>November</th><th>December</th><th>January</th><th>February</th><th>March</th><th>April</th><th>May</th></tr>
<tr><td rowspan="2">Rainfed system</td><td colspan="6">Hom Mali rice (Kao Dok Mali 105 Variety)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Glutinous rice (RD6 Variety)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Irrigated in wet season</td><td colspan="6">Hom Mali rice (Kao Dok Mali 105 Variety)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Glutinous rice (RD6 Variety)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Irrigated in dry season</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="5">Hom Mali rice (RD15 Variety)</td></tr>
</table>

Figure 5.3 Cropping calendar in the paddy field of Nam Mae Lao Basin (N)

With reference to the scope of the study, this research considers only Hom Mali rice.This study ignored glutinous rice (RD6 Variety) and other crop. As mentioned in section 5.1, in Nam Mae Lao basin under rainfed condition (Rw), the chief method used is sowing dry seeds, while sowing wet seeds is normally used in Iw and Id irrigated systems. Therefore, the cropping calendar of these methods as shown in Figure 5.4, 5.5 and 5.6, respectively. Normally paddy fields under rainfed condition have the 1st land preparation in November, more than 6 months before the 2nd land preparation because the farmers need to leave the paddy field for rice straw decomposition. Iw and Id systems, farmers do the 1st land preparation after finishing of harvesting, immediately.

No.	Time	Type of operation	Month																																																					
																																Growing Period of Hom Mali rice (Kao Dok Mali 105)																								
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1.	1st	land preparation	🟩																																																						
2.	2nd	land preparation																															🟩																								
3.	3rd	land preparation																															🟩																								
4.	1st	Sowing or Broadcasting																															🟩																								
5.	1st	Tillage																															🟩																								
8.	1st	Cutting grasses																																🟩																							
6.	1st	Pest and weed management																																🟩																							
7.	1st	Fertilizer application																																	🟩																						
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Figure 5.4 Rice cropping system under Rainfed condition with Sowing by dry seeded method in Nam Mae Lao basin

No.	Time	Type of operation	Month																																																				
																																Growing Period of Hom Mali rice (Kao Dok Mali 105)																								
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2	1st	land preparation																											🟩																													
3	1st	Soak Seeds																																	🟩																									
4	2nd	Water management(by Pumping)																																		🟩																								
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14	2nd	Cutting grasses																																																	🟩								
15	1st	Harvest&Thresh																																																		🟩							

Figure 5.5 Rice cropping system under Irrigation condition in Wet Season with Sowing by wet seeded method in Nam Mae Lao basin

No.	Time	Type of operation	Month																																																								
											Growing Period of Hom Mali rice (RD 15)																																															
			Nov				Dec				Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
1	1st	Water management(by Pumping)	🟩																																																						
2	1st	land preparation	🟩																																																						
3	1st	Soak Seeds										🟩																																													
4	2nd	Water management(by Pumping)											🟩																																												
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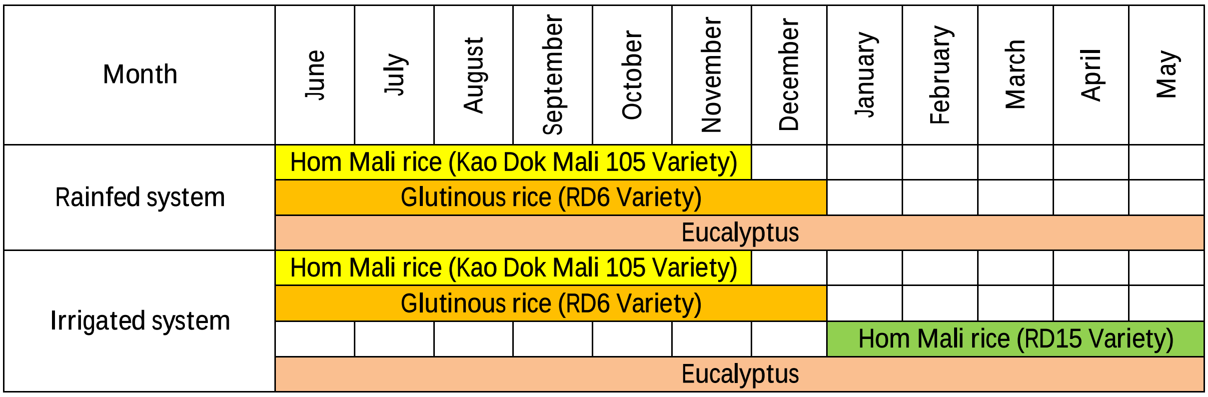
16	2nd	Cutting grasses																										🟩																													
17	1st	Harvest&Thresh																											🟩																												

Figure 5.6 Rice cropping system under Irrigation condition in Dry Season with Sowing by wet seeded method in Nam Mae Lao basin

5.2.2 Cropping calendar of the paddy field in Lam Sieo Yai basin (Northeast of Thailand)

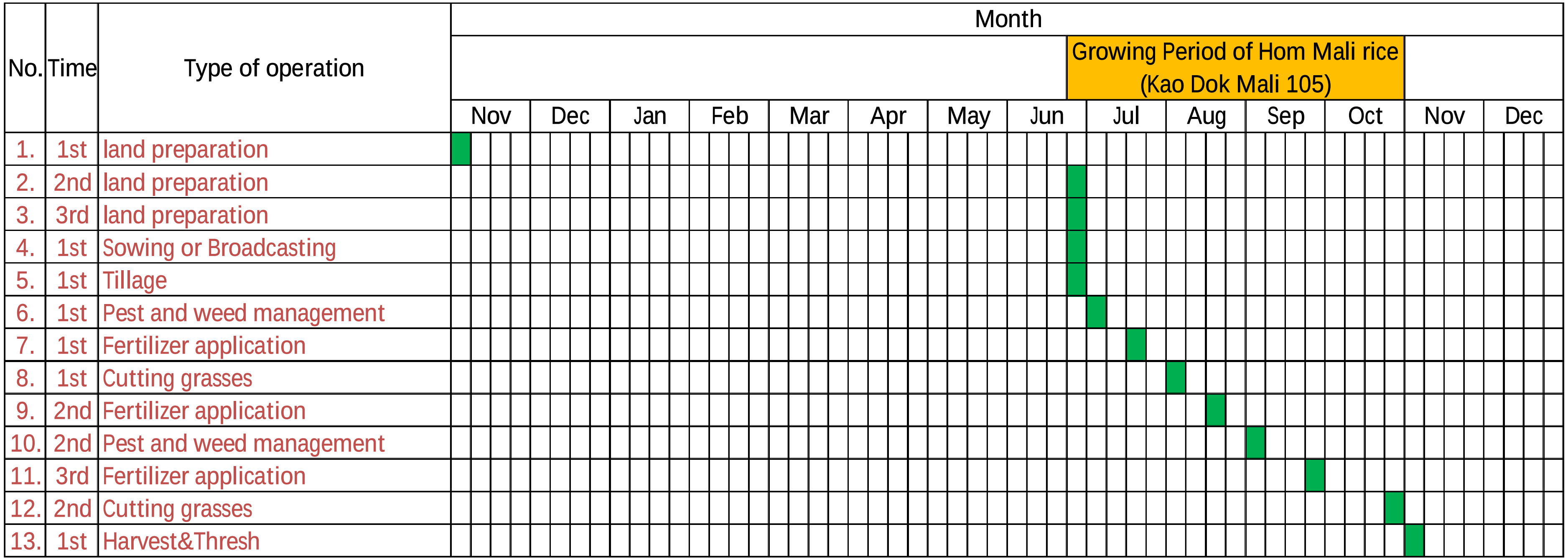
Figure 5.7 shows the cropping calendar in the paddy field of Lam Sieo Yai basin. In wet season both in rainfed and irrigated systems, there are two main varieties of rice grown (Kao Dok Mali 105 and RD6 Varieties) and in the dry season with limited time and water, farmers normally grows Hom Mali rice with RD15 variety. This study considered Kao Dok Mali 105 and RD 15 which are the main varieties of rice in wet and dry seasons, respectively. These three varieties are normally used in this study area. There is specific to both in rainfed and irrigated systems in Lam Sieo Yai basin where farmers also grow eucalyptus on the bund of paddy field. The eucalyptus can be sold to wood pulp companies, which produce paper from eucalyptus pulp.



Month	June	July	August	September	October	November	December	January	February	March	April	May
Rainfed system	Hom Mali rice (Kao Dok Mali 105 Variety)											
	Glutinous rice (RD6 Variety)											
	Eucalyptus											
Irrigated system	Hom Mali rice (Kao Dok Mali 105 Variety)											
	Glutinous rice (RD6 Variety)											
								Hom Mali rice (RD15 Variety)				
	Eucalyptus											

Figure 5.7 Cropping calendar in the paddy field of Lam Sieo Yai basin (NE)

As mentioned in section 5.1, in Lam Sieo Yai basin, the chief sowing method in all systems is direct seeding of dry seeds., Figures 5.8, 5.9, 5.10 show the cropping calendars foir those systems respectively. Like in Nam Mae Lao basin, paddy fields under rainfed condition are first land-prepared in November right after harvest and more than 6 months before the 2nd land preparation. This does not occur in irrigated systems.



No.	Time	Type of operation	Month																																																					
																																Growing Period of Hom Mali rice (Kao Dok Mali 105)																										
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1.	1st	land preparation	🟩																																																					
2.	2nd	land preparation																														🟩																								
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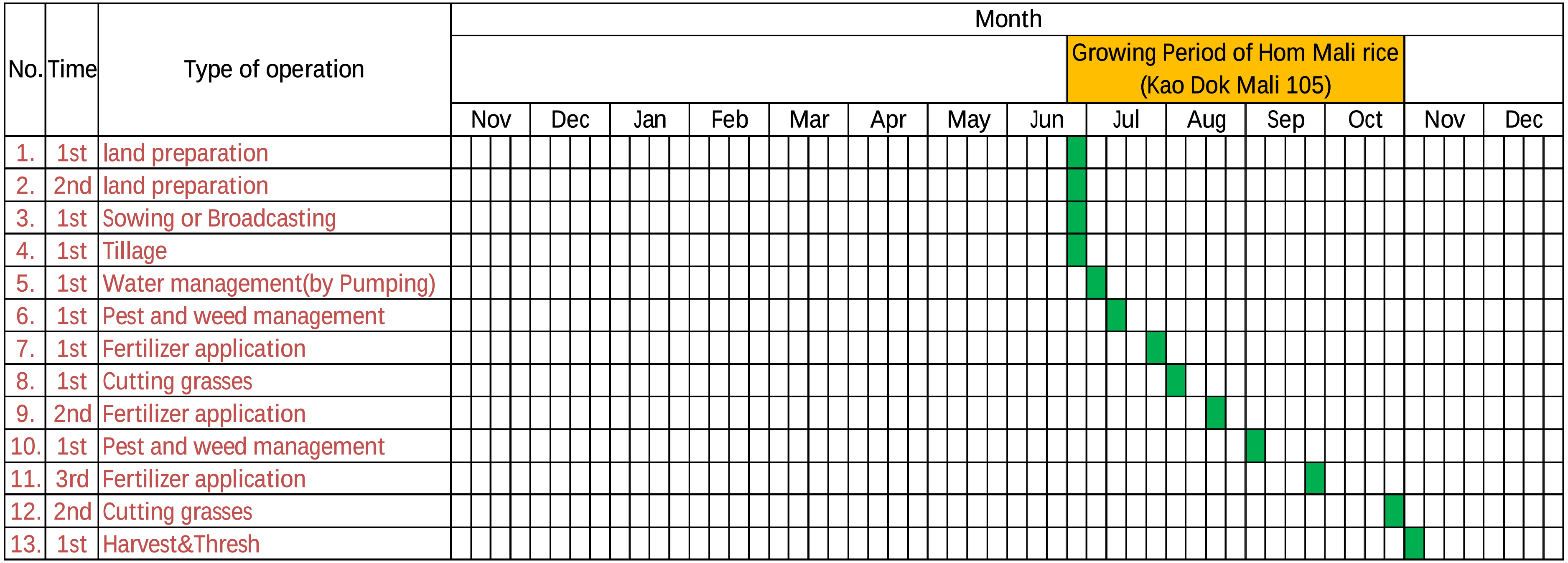
10.	2nd	Pest and weed management																																							🟩															
11.	3rd	Fertilizer application																																										🟩												
12.	2nd	Cutting grasses																																														🟩								
13.	1st	Harvest&Thresh																																															🟩							

Figure 5.8 Rice cropping system under Rainfed condition with Sowing by dry seeded method in Lam Sieo Yai basin



No.	Time	Type of operation	Month																																																					
																																	Growing Period of Hom Mali rice (Kao Dok Mali 105)																							
			Nov				Dec				Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
1.	1st	land preparation																																🟩																								
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6.	1st	Pest and weed management																																		🟩																						
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Figure 5.9 Rice cropping system under Irrigation condition in Wet Season with Sowing by dry seeded method in Lam Sieo Yai basin

No.	Time	Type of operation	Month																																																					
													Growing Period of Hom Mali rice (RD 15)																																										
			Nov				Dec				Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
1.	1st	land preparation											🟩																																											
2.	2nd	land preparation											🟩																																											
3.	1st	Sowing or Broadcasting											🟩																																											
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7.	1st	Fertilizer application														🟩																																							
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5.	1st	Water management(by Pumping)																		🟩																																					
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10.	1st	Pest and weed management																			🟩																																				
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13.	1st	Harvest&Thresh																											🟩																												

Figure 5.10 Rice cropping system under Irrigation condition in dry Season with Sowing by dry seeded method in Lam Sieo Yai basin

5.3 Cropping intensity of the paddy field

The concept of cropping intensity refers to the ratio of area covered with one crop over the total potential area croppable over one year (or percentage of the number of crops grown in a year or the fraction of the arable area that is harvested). The cropping intensity may exceed 100% where more than one crop is harvested each year over a given area.

Table 5.4 presents cropping intensities of rice plots in the selected basins, based on primary data. Cropping intensity in Nam Mae Lao and Lam Sieo Yai Basins under rainfed condition are 96% and 95%, respectively. Such figures reflect the facts that 1) these plots are cropped only once a year during the wet season, and 2) that the total area includes bunds (for ponding conditions), which are not planted with rice. It may be noticed that in the Northeast, many farmers actually grow eucalyptus on these bunds, therefore reaching 100% cropping intensity.

Under irrigation, rice may be grown twice a year in both basins. Therefore, cropping intensities exceed 100%: 192% and 150% in Nam Mae Lao and Lam Sieo Yai basin, respectively. Cropping intensity of paddy field in Nam Mae Lao basin is greater than cropping intensity of paddy field in Lam Sieo Yai basin because in dry season, farmers in the north can grow rice on the whole area but in the northeast, rice can be grown only 50% of the paddy area.

Table 5.4 Cropping intensity of selected basins

Rice cropping system	**Cropping intensity (%)**	
	Nam Mae Lao basin	**Lam Sieo Yai Basin**
Rainfed	96	100
Irrigated	192	150

5.4 Conclusions: What are the most salient features of rice cropping systems in selected basins?

Overall, the most important feature of these systems remains their relatively low yields, compared to a national (e.g. in Central Plains and with other varieties), regional and international references. Such yields obviously result in higher impacts and resource use when a mass-based functional unit is used in LCA. Other elements are worth noting, as follows.

5.4.1 The vanishing of transplanting and its consequences

In both basins, transplanting has been substituted for direct seeding, due to increased labor scarcity, and despite yield loss. Indeed, as shown in Table 5.2, transplanting guarantees higher yields, while direct seeding of wet (pre-soaked) seeds comes second, and seeding of dry seeds results in the lowest yields, under all water supply conditions, and in both basins. Sowing of dry seeds largely prevails in all cropping conditions in Lam Sieo Yai, while it only prevails under rainfed conditions in Nam Mae Lao. There, irrigation farmers favor the sowing of pre-soaked (wet) seeds.

As shown in Figure 5.1 and 5.2, these techniques incur different management sequences, especially in terms of land preparation, water requirements and management. Cropping calendars shown in Figure 5.4 to 5.10 focus on the main seeding methods, and highlight the early land preparation incurred by rainfed cropping in both basins, and in irrigated systems in the North, leading to the early incorporation of residues from the previous crop (more than 30 days before the cropping cycle starts), and therefore to changes in organic matter decomposition and methane emissions. As discussed in chapter 4 and shown in Table 4.18, such different results in different methane emission factors, according to IPCC's methods. Irrigated systems in the Northeast perform the first tillage, hence straw incorporation, right at the beginning of the cropping sequence and before the flooding, resulting in higher methane emissions. Finally, only rainfed systems in both basins have a long drying period prior to cropping (more than 180 days), resulting in a lower methane emission factor.

These differences in cropping systems partly explain the difference shown in environmental impacts, as discussed later in chapter 7.

5.4.2 The cropping intensity depends on water availability

Table 5.4 shows the cropping intensities observed in both basins. Paddy fields are all cropped during the wet season under rainfed conditions. Indeed, cropping intensity is almost 100%. Conversely, cropping intensity under irrigation is different. In the North (Nam Mae Lao), most fields that are cropped during the wet season, under irrigation that supplements rainfall, are also cropped in the following dry season. Such succession is permitted by favorable climatic conditions and well-endowed irrigation systems in dry season, hence a cropping intensity of 192%.

Conversely, water scarcity hits the Northeastern region (Lam Sieo Yai) during the dry season; only half of the plots that are irrigated in the wet season are also cropped in dry season.

These results, obtained from primary data and observations during the year 2010-2011, are fully consistent with the regional figures given in section 3.3.

Observations on water availability, plus interviews and observations of farmers' practices in both basins, resulted in defining the main field water management regime in all systems as "intermittent flooding, with multiple aeration" (as per IPCC terminology, 2006), except for wet season systems in the Northern basin (Rw and Iw) which are considered under "permanent flooding". As shown in Table 4.20, such choices have massive impacts on CH_4 field emission calculations, and therefore, results of the next sections on environmental impacts must been analyzed with caution and full awareness of this uncertainty.

CHAPTER 6

TECHNO-ECONOMIC PERFORMANCES

This chapter includes an assessment of the technical and economic performances of Hom Mali rice systems, based on the analysis of primary data in Lam Sieo Yai and Nam Mae Lao Basins. Rice cropping under wet season rainfed conditions, and under irrigation in dry and wet seasons were considered. All the indicators used are mentioned in Table 4.3.

6.1 Techno-Economic Performances of Nam Mae Lao basin

6.1.1 Utilization of production factors and performances per area cultivated

Table 6.1 shows the techno-economic performances of the three cropping systems per area cultivated (ha). The results highlight the low performance of rainfed rice systems (Rw), the production factor requirements of which are systematically higher than those of the two other systems; in addition, the Rw systems yielded significantly lower production.

The input of labour use is lower in rain-fed system because the requirement of labour due to the method to produce rice. The dry seeded method is normally applied in rainfed rice, on the other hand, the wet seeded method is needed in Iw and Id systems which require more labour for doing land preparation which requires blue water and pumping water progress. Therefore, the input of blue water to paddy field of Iw and Id systems are higher than rainfed systems. Therefore, there are the big variations among the samplings. The total energy required includes human power and differs slightly between systems for the same main reasons.

The high level of homogeneity of fertilizer and pesticide application practices within each cropping system was remarkable. All sampled farmers, advised by local officers of the Royal Irrigation Department, applied the same chemicals, doses and scheduling which are 625 kg of fertilizer per ha and 5.481 kg of active matter per ha.

This resulted in relatively homogeneous production costs per system; however, there were diverse outcomes in terms of yield (as shown in Table 6.2), therefore of gross and net income. Net income per system was wide-ranging, with the rainfed system being the least profitable and the most variable. Iw systems showed higher homogeneity of results and a potential for the higher yields and net income.

Figure B-1 (Appendix B) shows the diversity of production factors and performances per area cultivate recorded in the 60 cropping systems (year 2010).

6.1.2 Productivity of production factors and performances per mass of rice produced

Table 6.2 shows the productivities of production factors and the techno-economic performances of the three rice cropping systems. Overall, the results confirm that the productivities of most factors are higher in the Iw system, in which farmers produce less rice per l water unit. Interestingly, the overall of the productivities in the Rw system are lowest when compared to other systems, in which farmers produce more rice per 1 water unit and blue water unit. Iw and Id systems are also similar for factors, especially, green water and blue water productivities which are far from Rw system because there is small blue water that supply to Rw systems, but there is a big blue water for land prepare that needed to Iw and system and there is a very big blue water for land preparation and crop water requirement that supply to Id system.

Return on investment (mass of rice produced per production cost) is slightly higher in the Iw system compared to the Id system (0.174 kg/THB and 0.162 kg/THB, respectively) and is lowest in the Rw system (0.154 kg/THB). Median yields (land productivity) vary from 3,594 kg/ha in the Iw system to 3,438 in the Id system and 3,258 in the Rw system. Finally the amount of rice per net income unit is markedly lower in the Iw system (0.173 kg per THB earned as net income) and Id system (0.185 kg) compared to the Rw system (0.200 kg).

Figure B-2 (Appendix B) shows the diversity of productivity of production factors and performances per mass of rice produced recorded in the 60 cropping systems (year 2010). According to these diversities, it demonstrates that, in spite of quite homogeneous cropping practices (especially in terms of agrochemicals), yields are wide-ranging in all systems. Conditions during the dry season are less favourable temperature-wise and more uncertain and variable in terms of water management.

6.2 Techno-Economic Performances of Lam Sieo Yai basin

6.2.1 Utilization of production factors and performances per area cultivated

Table 6.3 shows the techno-economic performances of the three cropping systems per area cultivated (ha). The results highlight the low performances of dry-season irrigated rice systems (Id), the production factor requirements of which are systematically higher than those of the two other systems; in addition, the Id system yielded significantly lower production. This system also requires mostly blue water (irrigation water), while the other two rely predominantly on green water (natural stocks and flows). The Id system requires 3 pumping episodes on average to replenish ponding conditions in paddy fields; therefore, it requires more labour and energy (pumps).

Labour and pesticide requirements are markedly lower in rain-fed conditions due to lesser water management requirements and an absence of treatment against the golden snail (Pomacea canaliculata, which cannot reproduce during the cropless dry season of rain-fed plots). The total energy required includes human power and differs slightly between systems for the same main reasons.

According to Table 6.3 at blue water use, there is a big variation among the sampling because to produce rice, transplanting, wet and dry seeded methods can be used and transplanting and wet seeded methods need blue water for land preparation. Therefore, there is the big different between maximum and median value which the median bases on dry seeded method.

The high level of homogeneity of fertilizer and pesticide application practices within each cropping system was remarkable. All sampled farmers, advised by local officers of the Royal Irrigation Department, applied the same chemicals, doses and scheduling. This resulted in relatively homogeneous production costs per system; however, there were diverse outcomes in terms of yield (as shown in Table 6.4) and therefore of gross and net income. Net income per system was wide-ranging, with the Id system being the least profitable and the most variable. Iw systems showed higher homogeneity of results and a potential for the higher yields and net income.

Figure B-3 (Appendix B) shows the diversity of production factors and performances per area cultivate recorded in the 60 cropping systems (year 2010).

6.2.2 Productivity of production factors and performances per mass of rice produced

Table 6.4 shows the productivities of production factors and the techno-economic performances of the three rice-cropping systems. Overall, the results confirm that the productivities of most factors are higher in the Rw system, in which farmers produce more rice per labour unit, pesticide unit and total energy unit. Interestingly, the productivities in the Rw and Iw systems are also similar for factors such as fertilizer, total water and green water. According to this table at blue water use, there is a big variation among the sampling of Rw system because of the same reasons that are mentioned in the previous section.

Return on investment (mass of rice produced per production cost) is slightly higher in the Iw system compared to the Rw system (0.117 kg/THB and 0.114 kg/THB, respectively) and is lowest in the Id system (0.095 kg/THB). Median yields (land productivity) vary from 2,625 kg/ha in the Iw system to 2,375 in the Rw system and 2,188 in the Id system. Finally the amount of rice per net income unit is markedly lower in the Iw system (0.228 kg per THB earned as net income) and Rw system (0.248) compared to the Id system, in which farmers need to produce twice as much rice (0.662 kg) to obtain the same net income.

Figure B-4 (Appendix B) shows the diversity of productivity of production factors and performances per mass of rice produced recorded in the 60 cropping systems (year 2010). According to these diversities, it demonstrates that, in spite of quite homogeneous cropping practices (especially in terms of agrochemicals), yields are wide-ranging in all systems. Conditions during the dry season are less favourable temperature-wise and more uncertain and variable in terms of water management.

Table 6.1 Production factor use and techno-economic performances per area cultivated in selected rice cropping systems of Nam Mae Lao basin – year 2010

Techno-economic performance	**Reference Unit**	**Rainfed rice**			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		Ref. Unit/ha								
		Max.	**Median**	**min.**	**Max.**	**Median**	**min.**	**Max.**	**Median**	**min.**
Land	**ha**	1	1	1	1	1	1	1	1	1
Labour	**man hr.**	13.82	8.79	5.79	12.62	9.32	5.50	19.08	11.05	7.42
Fertilizer	**kg of fertilizer**	688	625	563	688	625	563	688	625	563
Pesticide	**kg of active matter**	5.48	5.48	2.66	5.48	5.48	2.74	5.48	5.48	2.74
Water	**m^3**	11,359	7,057	7,057	11,317	10,178	7,057	11,635	10,709	7,587
Green Water	**m^3**	8,071	7,055	7,055	8,071	7,055	7,055	2,730	2,728	2,728
Blue Water	**m^3**	3,288	1.99	1.39	3,246	3,123	1.23	8,905	7,981	4,859
Energy	**MJ**	20,832	19,447	16,996	20,103	19,085	18,345	20,727	19,478	18,739
Production cost	**THB**	22,394	21,169	18,605	22,404	21,113	19,208	22,549	21,277	19,445
Gross income	**THB**	46,429	37,500	32,143	47,857	41,429	35,714	42,857	39,286	35,714
Net income	**THB**	24,034	16,944	9,824	25,484	21,355	14,850	21,983	18,086	14,398

Note: THB = Thai Baht, currency of Thailand = approximately 0.033 US$ at the time of data collection (2010)

Table 6.2 Production factors’ productivities and techno-economic performances in selected rice cropping systems of Nam Mae Lao basin – year 2010

Techno-economic performance	**Reference Unit**	**Rainfed rice**			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		kg of paddy rice/Ref. Unit								
		Max.	**Median**	**min.**	**Max.**	**Median**	**min.**	**Max.**	**Median**	**min.**
Land productivity	**ha**	3,859	3,258	2,813	4,188	3,594	3,125	3,750	3,438	3,125
Labour productivity	**man hr.**	572.16	334.07	226.19	624.73	368.79	275.36	453.12	282.93	163.79
Fertilizer Productivity	**kg of fertilizer**	5.89	5	4.09	6.5	6	5	6.44	5.5	5
Pesticide productivity	**kg of active matter**	1,300	595.78	513.11	1,323	655.64	578.37	1,323	627.14	570.13
Water productivity	**m^3**	0.487	0.421	0.287	0.487	0.353	0.307	0.453	0.33	0.286
Green Water productivity	**m^3**	0.49	0.44	0.40	0.59	0.49	0.43	1.38	1.26	1.15
Blue Water productivity	**m^3**	2,476	1,566	0.99	2,786	1.18	1.00	0.71	0.44	0.37
Energy productivity	**MJ**	0.19	0.17	0.14	0.21	0.19	0.16	0.20	0.18	0.15
Production cost	**THB**	0.18	0.15	0.13	0.19	0.17	0.15	0.19	0.16	0.15
Gross income	**THB**	0.083	0.083	0.077	0.083	0.083	0.080	0.083	0.083	0.083
Net income	**THB**	0.29	0.20	0.16	0.21	0.17	0.16	0.22	0.19	0.17

Note: THB = Thai Baht, currency of Thailand = approximately 0.033 US$ at the time of data collection (2010)

Table 6.3 Production factor use and techno-economic performances per area cultivated in selected rice cropping systems of Lam Sieo Yai basin – year 2010

Production factors and performances	**Reference Unit**	**Rain-fed**			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		Ref. Unit/ha								
Land	**ha**	1	1	1	1	1	1	1	1	1
Labour	**man hr.**	8.49	6.63	5.68	15.23	11.95	8.01	16.45	16.45	11.25
Fertiliser	**kg of fertiliser**	625	625	625	687.5	687.5	687.5	687.5	687.5	687.5
Pesticide	**kg of active matter**	5.07	5.07	5.07	7.36	7.36	7.36	11.58	11.58	11.58
Total water	**m^3**	7,866	7,401	7,401	7,866	7,401	7,401	8,119	7,307	7,306
Green water	**m^3**	7,401	7,401	7,401	7,401	7,401	7,401	1,916	1,916	1,916
Blue water	**m^3**	465	0.25	0.29	465	0.24	0.20	6,203	5,391	5,391
Total energy	**MJ**	17,360	17,281	17,222	19,590	19,530	19,388	20,846	19,783	18,327
Production cost	**THB**	20,868	20,843	20,822	22,435	22,354	22,243	23,415	22,943	20,884
Gross income	**THB**	32,018	30,407	26,050	37,607	33,875	31,742	33,045	28,740	23,500
Net income	**THB**	11,196	9,564	5,182	15,364	11,521	9,193	10,102	5,325	2,616

Note: THB = Thai Baht, currency of Thailand = approximately 0.033 US$ at the time of data collection (2010)

Table 6.4 Production factors' productivities and techno-economic performances in selected rice cropping systems of Lam Sieo Yai basin – year 2010

Production factors and performances	**Reference Unit**	**Rain-fed**			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		kg of paddy rice/Ref. Unit								
Land	**Ha**	2,500	2,375	2,000	2,938	2,625	2,438	2,500	2,188	1,875
Labour	**man hr.**	440.37	358.49	235.47	366.60	219.69	160	222.22	133	160
Fertiliser	**kg of fertiliser**	4	3.80	3.2	4.27	3.82	3.55	3.64	3.18	2.73
Pesticide	**kg of active matter**	493	468	394	399	357	331	216	189	162
Total water	**m^3**	0.32	0.32	0.27	0.37	0.36	0.33	0.31	0.30	0.26
Green water	**m^3**	0.34	0.32	0.27	0.40	0.36	0.33	1.31	1.14	0.98
Blue water	**m^3**	9,500	6,933	5.37	12,483	10,985	6.31	0.41	0.40	0.35
Total energy	**MJ**	0.144	0.137	0.115	0.151	0.133	0.123	0.125	0.104	0.101
Production cost	**THB**	0.120	0.114	0.096	0.131	0.117	0.110	0.107	0.095	0.090
Gross income	**THB**	0.078	0.078	0.077	0.078	0.077	0.077	0.080	0.076	0.076
Net income	**THB**	0.386	0.248	0.223	0.265	0.228	0.191	0.717	0.411	0.247

6.3 Statistical analysis of cost and net income

Kruskal-Wallis test was carried out to test the significance of differences between costs, and between net incomes amongst the 3 cropping systems in both basins. The Kruskal–Wallis one-way analysis of variance by ranks is a non-parametric method for testing whether samples originate from the same distribution. It is used for comparing two or more samples that are independent. Fertilizer costs, pesticide costs, machinery costs and net income were studied as variables. All differences in distribution between the 3 systems in both basins and for all variables proved highly significant (p value ≤ 0.01).

Pair-wise tests were carried out with Student T-test on the same variables to test whether means calculated as per cropping system were significantly different from each other. Results are shown in table 6.5 and show that most means are significantly different, with the notable exceptions of pesticide costs in Nam Mae Lao.

Table 6.5 Student's T-test on cost and net income of both basins

Indicators	***p-value***					
	Nam Mae Lao			**Lam Sieo Yai**		
Data Set	**Rw & Iw**	**Rw & Id**	**Iw & Id**	**Rw & Iw**	**Rw & Id**	**Iw & Id**
Fertilizer Cost	**	**	n.s.	**	***	***
Pesticide Cost	n.s.	n.s.	n.s.	***	***	***
Machinery Cost	***	***	***	***	***	**
Net income	***	**	***	***	**	***

n.s. not significantly different (p>0.1)
* low significant difference at p≤0.1
** significant difference (p≤0.05)
*** highly significant difference (p≤0.01)

6.4 Discussion: diverse cropping circumstances result in contrasted and low techno-economic performances

6.4.1 Two basins under different climatic conditions

The two study basins are exposed to different precipitation and evapotranspiration conditions, as shown in Table 4.10 and Table 4.11. IWR calculations are based upon 30-year averages. It must be immediately noted that 2010-11 has been a rather wet period compared to 30 year average. This was particularly marked in the Northeastern region: annual precipitation of 2010 amounted to approximately 1,220mm in Lam Sieo Yai basin (Northeast) while 30-year average (1980-2009) is approximately 900mm. Annual precipitation in 2010 amounted to 1,800mm in Nam Mae Lao basin (North) while 30-year average (1980-2010) is approximately 1,730mm. Wet season was slightly more rainy, while the dry season was a bit drier than average.

Table 6.6 Rainfall data from the two study basins, for 2010 and 30-year averages (1980-2009)

Basins :	Lam Sieo Yai		Nam Mae Lao Basin	
Period	Rainfall depth (mm)		Rainfall depth (mm)	
	30-year average	2010	30-year average	2010
Yearly	886	1,219	1,729	1,803
Wet-season (July-October 2010)	708	896	1,127	1,372
Dry-season (February-May 2010)	117	192	273	262

Nam Mae Lao basin benefits from markedly higher effective rainfall and lower evapotranspiration, which did not require any irrigation in wet season of 2010. However, irrigation farmers indicated that under drier conditions (dry years), they have to occasionally pump water into their paddy fields as supplemental irrigation. Conversely, there was agricultural water deficit during the wet season in Lam Sieo Yai basin, which required supplemental irrigation, even under the favorable conditions of 2010. IWR are high in dry season in both basins, and especially high in Northeastern basin of Lam Sieo Yai (> 600mm for direct seeded rice, >680 for transplanted rice, in 2010). IWR in dry season are likely to be even higher in normal and drier years. Combined high IWR and seasonal water scarcity explain why cropping intensity remain low in dry season in Northeastern region, as discussed in chapter 5.

Water requirements modeling confirmed that transplanting technique requires more water than direct seeding. Besides limited labor availability, such factor might explain why farmers turn to direct seeding in both basins (see Table 5.1) under water scarcity conditions.

6.4.2 Similarities and differences between the two basins

Both basins have low yields compared to national average, regional and international records. For instance, Central Plains of Thailand show more intensified production patterns, with higher average yields (3.5t/ha), yet far from regional records of more than 5t/ha in Vietnam or South China, or international performers such as California, USA (8-9t/ha). Part of this may be explained by rice variety. As already said, Hom Mali is a high-quality, high-value but low-yielding, photoperiod-sensitive rice. Also, in each basin, one of the systems shows particularly lower yields, and draws down the overall performance.

In Nam Mae Lao basin, the low performance of rainfed rice systems (Rw) is highlighted. In the basin, rainfed systems are clearly less intensive systems, which still use dry-seed seedling method, while irrigation systems in both wet and dry season benefit sufficient water supply and care (wet-seed seedling).

In Lam Sieo Yai basin, Id systems are the low yielding ones. This is not related to seedling method since dry seed seedling now prevails in all systems, and results in lower yields overall. Rather, it was observed that conditions and practices are similar between Rw and Iw systems, while Id systems suffer from insufficient water supply and additional pests. Indeed, the rice-stem eater and virus-transmitter brown plant-hopper (Nilaparvata lugens, Homoptera: Delphacidae) does not exist yet in the North, but thrives during the dry season in the Northeast, forcing farmers to apply more insecticide (Isoprocarb) and lowering yields. As shown in table 5.2, of all seedling methods, the dry-seed seeding method results in the lowest yields. It is also the one that requires least water and labour, which explains its popularity in Northeast.

So in the two basins, the systems that concentrate most issues and yield lowest performances are different: rainfed systems in the North (Rw), dry-season irrigation systems (Id) in the Northeast. Interestingly, both these systems are the least implemented by farmers in both basins, respectively.

In both basins, the highest yielding system is Iw. Supplemental irrigation provided during the monsoon season, combined with high temperatures, ideally results in the highest performances of photosensitive Hom Mali rice. Photosensitivity -or the capacity to flowering homogenously when days get shorter (from September) regardless of slight shifts in planting times- makes also harvesting time more predictable, homogenous, and easier to manage. Conversely, brown plant-hopper thrives during the dry season and is one reason for lower yields.

In both basins, labor use and energy use are higher in Id systems because irrigation in dry seasons require more water pumping episodes on average to replenish ponding conditions in paddy fields; therefore, it requires more labor and energy. Combined with lower yields, these elements make Id systems least labor and energy productive.

Production costs per ha are quite homogenous across systems and basins. However, due to lower yields, net income is markedly lower in the Northeastern basin. Actually, farmers in Lam Sieo Yai basin pocket approximately half of what farmers earn in Nam Mae Lao basin, which ever system they practice. At the two ends of the scale of system performance, Iw systems earn 21,355 THB per ha in the North, while Id systems earn 5,325 THB per ha in the Northeast. In both basins, Iw systems earn the highest net income.

It must be kept in mind that these results refer to 2010, a relatively wet year. Techno-economic performances might be far worse for Id systems in a normal or drier year in the Northeast. These results tend to explain the lack of interest in dry season cropping by farmers in Northeast, a place of poverty, outmigration and livestock rearing during dry season.

6.4.3 Homogenous cropping practices; poor and contrasted performances

Farmers' practices proved surprisingly homogenous across cropping systems in both basins, showing particularly small variations in water use, and application of agrochemicals. The homogeneity in water use between systems in one same season is due to the modeling approach, yet the results are likely to be very different between seasons.

Production costs per ha illustrate such relative homogeneity of practices. The limited sample size may hide the actual diversity; also, farmers may have responded to questionnaire-based interviews in a generic way, focusing on recommendations they receive rather than on their actual varying practices. Indeed, in Thailand's irrigation projects, technical support is provided by local officers of the RID that manages the projects, in association with agro-chemical retailers; all tend to promote and disseminate blanket recommendations. Further, collective water management in irrigation systems, with a photosensitive rice, imposes synchronicity and commonality of practice, in single-crop systems where both rice physiology and climatic conditions prevail over individual contingencies and liberty. The homogeneity of practices is less comprehensible with regards to rainfed cropping systems, performed by individual farmers, least connected to RID. Small-scale paddy farmers often lack the education and own experience to challenge existing norms and to experiment. Thailand rice farmers are generally very abiding of norms and standards set up by authorities.

Strikingly, labour use shows much more diversity, although it is also dependent on water management. Labour mobilization in a cropping system typically refers to one individual farmer's decision and organization mode; contingencies and strategic choices can more fully materialize. In spite of the relative homogeneity of cropping practices, overall and per sub-cropping system, outcomes in both economic and environmental terms show significant diversity. Net income and global warming potential are particularly wide-ranging in the different systems. This variation mostly results from large differences in yields, overall and per sub-cropping system.

Yields and resulting net incomes are more diverse in Rw and Id systems compared to Iw systems, due to a lack of control of the water supply and a lack of water, respectively. Attempts to relate farmers' performances to several socio-economic factors at the household level (i.e., experience in farming, age, level of education) proved unsuccessful. Instead, it was observed that, while Id farmers usually try to refill their paddy fields three times per season, many do not actually obtain enough water (e.g., canal tail-enders). The precipitation levels of the dry season of 2010 were relatively high compared to 30-year average precipitation levels; the lack of water for Id system farmers could have been even more damaging to yields in normal or drier years. This would potentially result in lower yields, and increased differences in performances and impacts between wet season and dry season systems. The same reasoning applies to Rw systems, which showed relatively high performances and low impacts in 2010, but would perform well below Iw systems under drier conditions.

Table 6.7 shows the average crop water productivities (CWP) calculated for the different systems. CWP is often also referred to in literature as "water use efficiency" (Zwart and Baastianssen, 2004) is defined as the marketable crop yield over actual seasonal evapotranspiration (yield $kg.ha^{-1}$ / ET $m^3.ha^{-1}$); its unit is $kg.m^{-3}$. Therefore, CWP as an indicator focuses on how efficient is water used by the field crop itself, and ignores the efficiency of the whole water supply system.

Table 6.7 Average crop water productivity values (CWP in kg.m-3) in selected Hom Mali rice systems

Basins	Systems	CWP
Nam Mae Lao	Rw	0.625
	Iw	0.688
	Id	0.505
Lam Sieo Yai	Rw	0.438
	Iw	0.484
	Id	0.327

Results from both basins in Thailand point Id systems as the least water-efficient systems and Iw systems as the most water-efficient systems. Id systems in the Northeast are particularly low compared to others, on account of low yields. Yet, the most important fact is that crop water use efficiency in Thailand's Hom Mali cropping systems is very low overall, compared to international references. Different studies show that CWP ranges between 0.6 and 1.6 kg.m^{-3} (a literature review by Zwart and Bastiaanssen, 2004), between 0.4 and 1.6 kg.m^{-3} (Tuong and Bouman, 2003; focusing on lowland paddy rice). Doorenbos and Kassam (1979) found a CWP value of 1.1 kg.m^{-3}. Maximum values of 2.2 kg.m^{-3} were found in China (reported by Zwart and Bastiaanssen, 2004), under high yield conditions (10t/ha) and relatively low ET.

Compared to those international records, Hom Mali rice systems in Thailand are clearly inefficient in water use, due to low yields (with a diversity of non-water related limiting factors, including extensive cropping practices, and pest pressure), and also high ET conditions due to quasi-permanent flooding. Alternate wetting / drying conditions in paddy fields seems to lead to higher CWP (Zwart and Bastiaanssen, 2004).

6.4.4 Productivity of agrochemicals

Table 6.8 shows the performances related to nitrogen application in all systems and basins, based upon median values. As discussed in the previous section, agrochemical application doses are very homogenous, rather high (usually-recommended applications range between 120-150 kg N per ha), yet leading to contrasted yields. Apparent N recovery efficiency (ANR; proportion of N applied that is found in harvested parts) is approximately 20% in all systems in the North, and closer to 15% in the Northeast.

Literature admits that flooded rice generally recovers 20 to 40% of nitrogen (Vlek and Byrnes, 1986) while other field crops commonly recover between 40 to 60%. Our systems' ANR are therefore low, especially in the Northeast. The seedling method that prevail there might explain the low performance of N application; Qi et al. (2012) found in China that dry-seed direct seedling associated with early urea application led to important loss through volatilization. While adopting massively dry-seed direct seedling in recent times, due to labour shortage, farmers in the Northeast have not adapted yet other practices of the cropping system. Qi et al. (2012) successfully tested alternative fertilization methods which reduced volatilization and improved ANR efficiency, such as delayed urea application, substitution of urea by ammonium sulfate as N application at planting time. Other alternatives include "deep placement" of urea pellets (supergranules) instead of regular surface broadcasting at planting time (Vlek and Byrnes, 1986); this technique is known yet not spread enough in Thailand.

Table 6.8 Performances related to nitrogen application in the selected systems of Nam Mae Lao and Lam Sieo Yai basins (based on median data; year 2010)

	Basins	Nam Mae Lao			Lam Sieo Yai		
	Rice cropping systems	Rw	Iw	Id	Rw	Iw	Id
Yield	t/ha	3.26	3.59	3.44	2.38	2.63	2.19
N application	kg N /ha	192	192	192	192	202	202
Harvested grain N content	kg N /ha	40.1	44.2	42.3	29.2	32.3	26.9
ANR efficiency	N%	20.9	23.0	22.0	15.2	16.0	13.3
N Productivity	kg rice /kg N	16.95	18.70	17.89	12.36	13.00	10.84

Also, these results contradict the long established fact of decreased yield response to N in wet season due to reduced solar radiation in combination with high relative humidity and increased disease and insect incidence (Vlek and Byrnes, 1986). Actually wet season irrigated systems show the highest yields in both basins respectively. In the Northeast, it may be explained by insufficient water supply and brown plant-hopper attacks; both factors being hardly a problem in the North.

Table 6.9 shows the pesticide productivities of Nam Mae Lao and Lam Sieo Yai basins, respectively. Results confirm the previously established productivity rankings; Rw systems in the North and Id systems in the Northeast show lesser productivity of all pesticides used. The overall low diversity of agrochemicals used must be underlined. In the North, farmers commonly only use one herbicide (glyphosate-based). In the Northeast, recent invasions of brown plant-hopper force farmers to use an insecticide (isoprocarb-based), which productivity is particularly low in dry season, when attacks are more severe. Golden snail (*Pomacea canaliculata* -Mesogastropoda: Pilidae) control must be performed with metaldehyde in the Northeast in fields that are irrigated all year round, because the snail reproduces during the dry season in irrigated fields. In Rw fields, which are left uncropped during the dry season, there is no need for protection. Surprisingly, snail damages are not deemed serious enough by farmers in the North, and most do not metaldehyde for snail control, despite the prevailing year-round irrigation systems.

Table 6.9 Productivity values of pesticides in the selected systems of Nam Mae Lao and Lam Sieo Yai basins (kg rice / g active ingredient; based on median data; year 2010)

Basins	Nam Mae Lao			Lam Sieo Yai		
Rice cropping systems	Rw	Iw	Id	Rw	Iw	Id
Glyphosate	13.20	14.42	13.45	15.63	10.20	8.62
Isoprocarb	n.a.	n.a.	n.a.	84.75	92.59	46.73
Metaldehyde	n.a.	n.a.	n.a.	n.a.	16.67	13.89

n.a. = no application

6.4.5 Conclusion

The two basins are exposed to contrasted conditions. Nam Mae Lao basin benefits more rainfall, and is immune so far from the brown plant-hopper. In this Northern basin, irrigation systems are prevailing, with all-year round cropping and highest performances. Rainfed systems are fewer, and perform at lower levels, on all productivity indicators.

On the contrary, Lam Sieo Yai basin suffers dry season water scarcity, and damages by two prevailing pests: brown plant-hopper in dry season, and golden snail in wet season in fields that are irrigated all-year round. Under such conditions, uncontrolled irrigation in wet season (Rw systems) prevails. Id systems are few and perform at lowest levels, on all productivity indicators. Overall, crop water productivity is very low.

The next chapter investigates the environmental impacts that result from these contracted cropping conditions.

CHAPTER 7

ENVIRONMENTAL IMPACTS

This chapter includes the results of LCI, LCIA and provides the environmental impacts (mid-point indicators) of Hom Mali rice systems in both selected basins.

7.1 Inventory results

7.1.1 Field Operations, inputs and resource use

Field operations

Field operations required for rice cultivation include: soil preparation (tillage), sowing, fertilizer application, pesticide application, water management, and harvesting. Each operation has been documented in each studied farm (a given plot) in terms of equipment used, amount used (dose and timing), area of application, schedule (within a crop calendar), and cost. All data were related to area cropped and mass of rice produced as functional units, as shown in Table 7.1a. and Table 7.1b respectively. From Table 7.1a, we can observe that the model entries for mechanical field operations of rainfed rice cropping systems are higher than the other two systems, except for water management which is higher in Id systems. As shown in Table 7.1b, Id systems show the highest of all the field operation data and then were followed by Rw and Iw systems, respectively.

Fertilizers

Doses, types of fertilizers were estimated using personal communications with farmers. The percentage of nutrient (N-P-K) present in each fertilizer and the amount used during operation to produce unit kg of production are mentioned in Table 7.2a and Table 7.2b. There are three main fertilizers that are used: Urea (46-0-0), 15-15-15 and 16-20-0 are used in Nam Mae Lao basin and Urea (46-0-0), 15-15-15 and 16-16-8 are used in Lam Sieo Yai basin. Urea is the most commonly used one and largely prevails.

Pesticides

The pesticides application doses and types were collected from personal communication with farmers in the fields. Commercial pesticides were modeled according to the active ingredients and the inventory data from Ecoinvent database (Table 7.3a and Table 7.3b). In some cases, no precise match was found and an active ingredient of a similar chemical class was adopted. From the observation, in the cropping systems under study, the pesticides typically used include a molluscicide (solid pellets, metaldehyde-based), an insecticide (liquid, isoprocarb-based with $CaCO_3$ as humectant additive) and a herbicide (liquid, glyphosate-based,). Liquid, isoprocarb-based with $CaCO_3$ is only used in Lam Sieo Yai basin.

Water Use

Irrigation data use as input data for LCA model, irrigation data use in the model which is calculated using virtual water and water footprint concepts, volume water use (sum of green water and blue water) to produce 1 kg of rice. The amounts of water use to produce 1 kg of paddy Hom Mali rice are shown in Table 7.1a and Table 7.1b which show that dry-season irrigated rice under both basins have the highest of the total water used and then were followed by Rw and Id systems, respectively.

Seeds

Input raw data, seed application rate was taken from the primary data. The application rate of seed varies between 93 and 125 kg/ha and the variation of seed application rate of each rice cropping system is shown in Table 7.4. In Nam Mae Lao basin, to produce 1 kg of rice, 0.0339 to 0.0364 kg of seeds are needed and 0.0395 to 0.0571 kg of seeds are needed in Lam Sieo Yai basin.

7.1.2 Direct field emissions

As mentioned above, the most important and impacting direct field emissions in paddy rice production include air emissions of methane, nitrous oxide, nitrogen oxides, and ammonia, as well as emissions of phosphorus and nitrates to water. Also, pesticides losses occur. Table 7.5a and Table 7.5b show the direct emissions from the paddy field. Emissions to air proved relatively homogeneous across all three systems, with the notable exception of methane emissions.

In Lam Sieo Yai basin, Rw systems emit a median amount of 76 g CH_4 per kg of paddy rice, compared with 158 g and 176 g for Iw and Id systems, respectively. Lower CH_4 emissions in rain-fed conditions relate first to the water regime in the pre-season before the cultivation period (non-flooded conditions for more than 180 days) and second to the management of organic residues (incorporated more than 30 days before the cultivation). In Nam Mae Lao basin, Rw systems emit a median amount of 76 g CH_4 per kg of paddy rice, compared with 103 g and 56 g for Iw and Id systems, respectively. Lower CH_4 emissions in dry season irrigated conditions because, owing to intermittent flooding with the multiple aeration phases. Rw and Iw systems are under the continuous flooding which generate more CH_4 emissions. Also, higher CH_4 emissions in wet season irrigated conditions relate to the water regime in the pre-season before the cultivation period, which are shorter than the other two systems (non-flooded conditions for less than 180 days). CH_4 emission figures broadly concur with those of the IPCC (2006), which reports that approximately 120 g of CH_4 are released into the atmosphere for 502 each kg of rice produced. Blengini & Busto, 2009 reported that according to Regione Piemonte (2005), in Italy, a value of 48 g of methane per kg of paddy rice was used in the LCA model. In 2012, Wang et al., 2012 reported the methane per kg of paddy rice in Chian was about 62 120 g of CH_4. The CH_4 emissions from other references seem to lower than this study; however the results reveal significant local differences based on cropping systems and water management practices.

With regard to emissions to water of Lam Sieo Yai basins, Id systems systematically emit more nitrates, phosphates, and agro-chemicals per both functional units, on account of the overall lower productivity of chemical inputs and Rw systems in Nam Mae Lao basin have the overall highest emissions to water and soil.

Table 7.1a LCI of paddy Hom Mali rice: model entries for mechanical field operations of rice cropping systems in Nam Mae Lao basin

Field process	**Database entry**	**Reference unit**	**Quantity (Reference unit/1 kg of paddy Hom Mali rice)**								
			Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Tillage operations	Tillage, ploughing	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04
Tillage operations	Tillage, rolling	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04
Sowing	Sowing	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04
Water management	Irrigating	m^3	9.19E-01	1.47E-04	7.02E-05	9.60E-01	8.14E-01	4.98E-05	2.23E+00	1.95E+00	1.15E+00
Fertilizing	Fertilizing	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04
Application of plant protection products	Application of plant protection products, by field sprayer	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04
Harvesting	Combine harvesting	ha	3.56E-04	3.07E-04	2.59E-04	3.20E-04	2.78E-04	2.39E-04	3.20E-04	2.91E-04	2.67E-04

Table 7.1b LCI of paddy Hom Mali rice: model entries for mechanical field operations of rice cropping systems in Lam Sieo Yai basin

Field process	**Database entry**	**Reference unit**	**Quantity (Reference unit/1 kg of paddy Hom Mali rice)**								
			Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Tillage operations	Tillage, ploughing	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04
Tillage operations	Tillage, rolling	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04
Sowing	Sowing	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04
Water management	Irrigating	m^3	3.15E+00	2.65E+00	2.52E+00	2.89E+00	2.68E+00	2.40E+00	3.87E+00	3.32E+00	2.90E+00
Fertilizing	Fertilizing	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04
Application of plant protection products	Application of plant protection products, by field sprayer	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04
Harvesting	Combine harvesting	ha	5.00E-04	4.21E-04	4.00E-04	4.10E-04	3.81E-04	3.40E-04	5.33E-04	4.57E-04	4.00E-04

Table 7.2a LCI of paddy Hom Mali rice: model entries for fertilizers of rice cropping systems in Nam Mae Lao basin

Commercial Name	**Active Ingredient**	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
		Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Hua-Wua-Kun-Tai (46-0-0)	Urea, as 46%N	0.11	0.10	0.08	0.10	0.09	0.07	0.10	0.09	0.08
Hua-Wua-Kun-Tai (15-15-15)	15%N – 15%P_2O_5 – 15%K_2O	0.07	0.05	0.04	0.05	0.04	0.03	0.05	0.04	0.03
Hua-Wua-Kun-Tai (16-20-0)	16%N – 20%P_2O_5 – 0%K_2O	0.07	0.05	0.04	0.05	0.04	0.03	0.05	0.04	0.03

Table 7.2b LCI of paddy Hom Mali rice: model entries for fertilizers of rice cropping systems in Lam Sieo Yai basin

Commercial Name	**Active Ingredient**	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
		Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Hua-Wua-Kun-Tai (46-0-0)	Urea, as 46%N	0.156	0.132	0.125	0.128	0.119	0.106	0.167	0.143	0.125
Hua-Wua-Kun-Tai (15-15-15)	15%N – 15%P_2O_5 – 15%K_2O	0.078	0.066	0.063	0.077	0.071	0.064	0.100	0.086	0.075
Hua-Wua-Kun-Tai (16-16-8)	16%N – 16%P_2O_5 – 8%K_2O	0.078	0.066	0.063	0.077	0.071	0.064	0.100	0.086	0.075

Table 7.3a LCI of paddy Hom Mali rice: model entries for pesticides of rice cropping systems in Nam Mae Lao basin

Associated chemical class in Ecoinvent	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
	Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
	Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Glyphosate	9.09E-05	7.58E-05	3.41E-05	8.18E-05	6.93E-05	3.53E-05	8.18E-05	7.44E-05	3.53E-05
Metaldehyde	5.56E-05	4.55E-05	0	4.55E-05	4.17E-05	2.16E-05	5.00E-05	4.55E-05	2.16E-05

Table 7.3b LCI of paddy Hom Mali rice: model entries for pesticides of rice cropping systems in Lam Sieo Basin basin

Associated chemical class in Ecoinvent	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
	Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
	Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Glyphosate	7.67E-05	6.46E-05	6.13E-05	1.05E-04	9.74E-05	8.70E-05	1.36E-04	1.17E-04	1.02E-04
Calcium carbonate	7.97E-05	6.71E-05	6.38E-05	6.54E-05	6.07E-05	5.43E-05	1.42E-04	1.21E-04	1.06E-04
Metaldehyde	-	-	-	6.41E-05	5.95E-05	5.32E-05	8.33E-05	7.14E-05	6.25E-05

Table 7.4 Seed application rate of paddy Hom Mali rice of rice cropping systems in selected basins

			Lam Sieo Yai basin	**Nam Mae Lao basin**
Seed application rate (kg/1 kg of paddy Hom Mali rice)	**Rainfed**	**Max.**	0.047	0.044
		Median	0.040	0.036
		Min.	0.038	0.027
	Wet-season irrigated rice	**Max.**	0.051	0.036
		Median	0.048	0.034
		Min.	0.043	0.025
	dry-season irrigated rice	**Max.**	0.067	0.040
		Median	0.057	0.036
		Min.	0.053	0.025

Table 7.5a Direct field emissions of paddy Hom Mali rice of rice cropping system in Nam Mae Lao basin: model entries

Direct emission		**Reference Unit**	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
			Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Emission to air	**Methane (CH_4)**	kg CH_4	8.42E-02	7.53E-02	6.49E-02	1.15E-01	1.03E-01	9.34E-02	5.96E-02	5.57E-02	5.24E-02
	N_2O	kg N-N_2O	2.70E-04	2.30E-04	1.90E-04	2.40E-04	2.00E-04	1.80E-04	2.40E-04	2.20E-04	2.00E-04
	NO	kg N-NO	1.60E-04	1.30E-04	1.10E-04	1.40E-04	1.20E-04	1.10E-04	1.40E-04	1.30E-04	1.20E-04
	NH_3	kg N-NH_3	1.93E-02	1.64E-02	1.34E-02	1.73E-02	1.48E-02	1.30E-02	1.73E-02	1.57E-02	1.44E-02
Emission to water	**Nitrates**	kg N	3.61E-02	2.73E-02	2.06E-02	2.85E-02	2.17E-02	1.91E-02	2.85E-02	2.48E-02	2.06E-02
	Phosphorus	kg P	1.85E-02	1.35E-02	8.36E-03	1.27E-02	9.72E-03	6.80E-03	1.42E-02	1.08E-02	7.21E-03
	Glyphosate	kg	4.54E-02	3.79E-02	1.70E-02	4.09E-02	3.47E-02	1.76E-02	4.09E-02	3.72E-02	1.76E-02
	Metaldehyde	kg	2.78E-02	2.27E-02	0.00E+00	2.27E-02	2.08E-02	1.08E-02	2.50E-02	2.27E-02	1.08E-02
Emission to soil	**Glyphosate**	kg	4.54E-02	3.79E-02	1.70E-02	4.09E-02	3.47E-02	1.76E-02	4.09E-02	3.72E-02	1.76E-02
	Metaldehyde	kg	2.78E-02	2.27E-02	0.00E+00	2.27E-02	2.08E-02	1.08E-02	2.50E-02	2.27E-02	1.08E-02

Table 7.5b Direct field emissions of paddy Hom Mali rice of rice cropping system in Lam Sieo Yai basin: model entries

Direct emission		**Reference Unit**	**Quantity (kg/1 kg of paddy Hom Mali rice)**								
			Rainfed			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
Emission to air	**Methane (CH_4)**	kg CH_4	8.67E-02	7.59E-02	7.31E-02	1.65E-01	1.59E-01	1.49E-01	1.94E-01	1.76E-01	1.63E-01
	N_2O	kg N-N_2O	3.70E-04	3.10E-04	3.00E-04	3.20E-04	2.90E-04	2.60E-04	4.10E-04	3.50E-04	3.10E-04
	NO	kg N-NO	2.20E-04	1.80E-04	1.70E-04	1.80E-04	1.70E-04	1.50E-04	2.40E-04	2.10E-04	1.80E-04
	NH_3	kg N-NH_3	2.66E-02	2.24E-02	2.13E-02	2.19E-02	2.04E-02	1.82E-02	2.85E-02	2.44E-02	2.14E-02
Emission to water	**Nitrates**	kg N	5.04E-02	4.05E-02	3.79E-02	4.27E-02	3.88E-02	3.33E-02	5.73E-02	4.74E-02	3.99E-02
	Phosphorus	kg P	1.94E-02	1.55E-02	1.45E-02	1.90E-02	1.73E-02	1.49E-02	2.64E-02	2.19E-02	1.86E-02
	Glyphosate	g	3.83E-02	3.23E-02	3.07E-02	5.24E-02	4.87E-02	4.35E-02	6.82E-02	5.84E-02	5.11E-02
	Calcium carbonate	g	3.98E-02	3.36E-02	3.19E-02	3.27E-02	3.04E-02	2.71E-02	7.08E-02	6.07E-02	5.31E-02
	Isoprocarb	g	7.03E-03	5.92E-03	5.63E-03	5.77E-03	5.36E-03	4.79E-03	1.25E-02	1.07E-02	9.38E-03
	Metaldehyde	g	-	-	-	3.21E-02	2.98E-02	2.66E-02	4.17E-02	3.57E-02	3.13E-02
Emission to soil	**Glyphosate**	g	3.83E-02	3.23E-02	3.07E-02	5.24E-02	4.87E-02	4.35E-02	6.82E-02	5.84E-02	5.11E-02
	Calcium carbonate	g	3.98E-02	3.36E-02	3.19E-02	3.27E-02	3.04E-02	2.71E-02	7.08E-02	6.07E-02	5.31E-02
	Isoprocarb	g	7.03E-03	5.92E-03	5.63E-03	5.77E-03	5.36E-03	4.79E-03	1.25E-02	1.07E-02	9.38E-03
	Metaldehyde	g	-	-	-	3.21E-02	2.98E-02	2.66E-02	4.17E-02	3.57E-02	3.13E-02

7.2 Environmental impacts

7.2.1 Environmental impacts of paddy rice in Nam Mae Lao basin

As discussed in the methodology section, the following impact categories were addressed: global warming potential (GWP_{100}), eutrophication (EP), acidification (AP), ozone depletion (ODP), freshwater aquatic ecotoxicity (FAETP) and water use (WU), land use (LU) and energy use (EU). Water Deprivation Potential (WDP) as an impact category is considered in the next chapter. Table 7.6 and Table 7.7 show the indicators relevant to the LCA model for 1ha of cultivated area and 1 kg of paddy rice in a Nam Mae Lao basin, respectively.

In all impact categories except GWP_{100}, Iw systems show the lower impacts per ha and per 1 kg of rice than Rw and Id systems, with the latter having the highest impacts.

As it can be seen in Table 7.7, to produce 1 kg of paddy Hom Mali rice under Id system, 2.15 kg CO_2-eq has to be generated and followed by 2.24 kg CO_2-eq of rain-fed rice and 2.90 kg CO_2-eq of Iw system. GWP_{100} is less in Id and high in Iw systems because of the lower and higher CH_4 emissions, respectively. The reasons have been given in the previous section and refer to direct field emissions and cropping practices.

Eutrophication potentials are homogenous and varies between 0.060 kg PO_4-eq in Rw systems, 0.045 kg PO_4-eq in Iw systems, and 0.050 kg PO_4-eq in Id systems. The reason of higher EP in Rw might be the higher input of fertilizers per 1 kg of paddy rice into the systems (see Table 7.2a) and lower yield in Rw systems.

In terms of acidification potential result, 0.029, 0.027 and 0.031 kg SO_2-eq were released by producing rice under Rw, Iw and Id conditions, respectively, which are not quite different when compared among the rice cropping systems because the application rates of fertilizer in each rice cropping system are not much different much and provide similar nitrates and phosphorus emissions to water.

Ozone depletion potential of dry-season irrigated rice has the highest value because of water management with pumping 3 times. Freshwater aquatic ecotoxicity is high in Iw systems because of higher input of metaldehyde when compared to other systems.

Id systems require more blue water (irrigated water) than other systems. Results are similar on energy use in all systems. Small differences are only due to rice production (yield).

Land use indicators directly inversely refer to yields, which are lower in Rw systems, higher in Iw systems.

Figure 7.1 reports a contribution analysis on rain-fed paddy rice, showing the relative contribution of cropping subsystems to each impact category. Direct field emissions to air and water have overwhelmingly contributed to AP, EP, GWP_{100} and FAETP. Field operations, meaning operations requiring the use of machinery and equipment (including water pumping, and the manufacturing of all equipment) contributes 20% of all energy use and a large part of ODP. Fertilizer application and manufacturing contribute a majority of total energy use, a large part of ODP, FAETP, and a marginal amount of AP, EP and

GWP_{100}. Pesticide application and manufacturing contributes to total energy use. Rice seeds contribute marginally to FAETP and EU. Pesticide application requires small amounts of water, and the main contributor to WU remains crop water use. Overall, direct field emissions are contributing a main part of output-related impact categories at local and regional scales (AP, EP, FAETP) and on the global scale (GWP_{100}); they mostly depend on water management practices for methane emissions, and both agro-chemical and water management for other emissions. Contribution analysis of the two other irrigated systems show the same structure and overall contributions, although total water use in Id systems results mostly from blue water use (irrigation water), while WU in Iw systems results mostly from the green water use (natural stocks and flows) which can be observed from Figure 7.2 and Figure 7.3.

7.2.2 Environmental impacts of paddy rice in Lam Sieo Yai basin

Table 7.8 and Table 7.9 show the indicators related to the LCA model for 1ha of cultivated area and 1 kg of paddy rice in a Lam Sieo Yai basin, respectively. In all other impact categories, Rw systems systematically show lower impacts per ha than Iw and Id systems, with the latter having the highest impacts. However, AP, ODP and total water use are of the same magnitude across systems.

As it can be seen in Table 7.9, to produce 1 kg of paddy Hom Mali rice under rainfed system, 2.97 kg CO_2-eq has to be generated and followed by 4.87 kg CO_2-eq of wet-season irrigated rice and 5.55 kg CO_2-eq of dry season irrigated rice. GWP_{100} is less in rainfed rice because of the lower CH_4 emissions, owing to the longer pre-season with non-flooding conditions and also the longer time of organic amendment which is straw incorporated into the soil before the cultivation time.

The results of eutrophication potential vary between 0.075kg PO_4-eq for Rw rice, 0.079 kg PO_4-eq was generated from Iw rice and 0.099 kg PO_4-eq was released from Id rice. In terms of acidification potential result, 0.044, 0.040 and 0.049 kg SO_2-eq were released by producing rice under Rw, Iw and Id conditions, respectively, which are not quite different when compared among the rice cropping systems because the application rate of fertilizer in each rice cropping system are not difference much and provides almost the same of nitrates and phosphorus emissions to the water.

As shown in Table 7.9, ozone depletion potential results vary between 0.061 to 0.096 mg CFC-11-eq according to the rice cropping systems. ODP of Id systems is the the highest because they require more water management by pumping 3 times.. Freshwater aquatic ecotoxicity is less in rainfed rice because farmers do not use metaldehyde to get rid of golden apple snail, as explained earlier.

To produce 1 kg of paddy rice, 2.65, 2.68 and 3.32 m^3 of water are required by Rw, Iw and Id systems, respectively. Id systems require more irrigated water or blue water than the other two systems. Results are similar with regards to energy use because of pumping needs. Land use reflects the yields, which are higher in Iw systems, followed by Rw. Id recorded significantly lower yields in 2010.

Overall, Rw and Iw systems tend to show similar impacts, while Id systems have higher impacts, partly due to lower yields, and higher water and pumping needs. Total energy use is higher in Id systems (9.635 MJ per kg rice) compared to Iw and Rw systems (7.5 and 7.285, respectively).

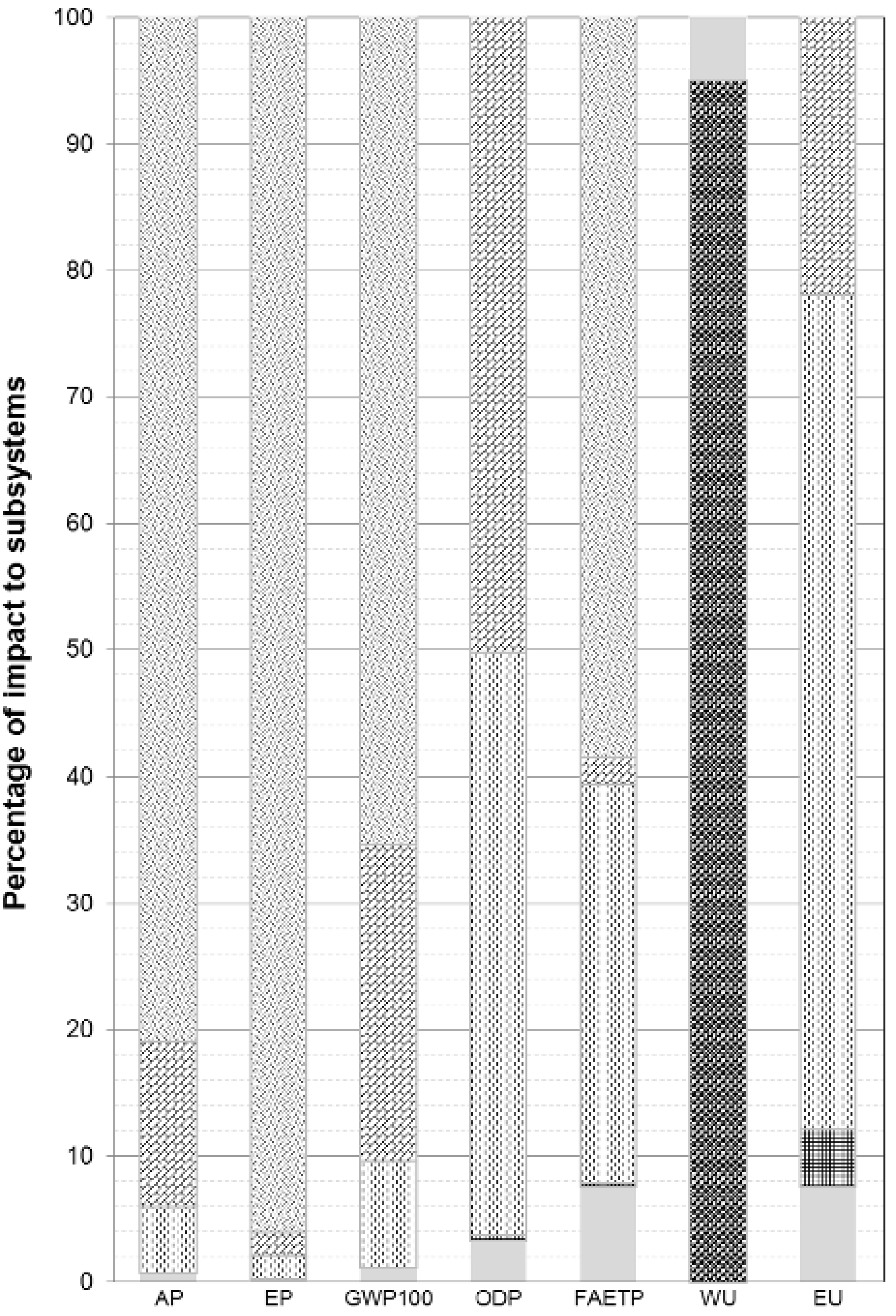
Figure 7.4 to Figure 7.6 report the contribution analysis of Rw, Iw and Id systems, respectively. All the systems show similar structure in terms of contribution. Direct field emissions to air and water are the main contributors to AP, EP, GWP_{100} and FAETP. Field operations contribute 20% of all energy use and a large part of ODP. Fertilizer application and manufacturing are the majority contributor of total energy use, a large part of ODP, FAETP, and a marginal amount of AP, EP and GWP_{100}. Pesticide application and manufacturing also contribute a lot to total energy use. Pesticide application requires small amounts of water, and the main contributor to WU remains crop water use. Rice seeds contribute marginally to FAETP and EU. Overall, direct field emissions are the majority contributor to output-related impact categories at local and regional scales (AP, EP, FAETP) and on the global scale (GWP_{100}), which mostly depend on water management practices for methane emissions, and both agro-chemical and water management for other emissions.

Table 7.6 Environmental impact indicators in selected rice cropping systems of Nam Mae Lao basin – year 2010, results expressed per ha cultivated

Impact indicator		**Reference unit**	**Rain-fed**			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
			Ref. Unit/ha								
Output-related indicators	**GWP_{100}**	**kg CO_2-eq**	8,136	7,054	6,778	11,223	10,682	9,866	7,763	7,548	6,656
	EP	**kg PO_4-eq**	226	188	140	202	170	128	2,162	175	134
	AP	**kg SO_2-eq**	100	96	94	102	100	95	1,083	106	101
	ODP	**mg CFC-11-eq**	175	136	101	159	156	134	189	186	158
	FAETP	**kg 1,4-DB eq**	484	265	166	492	479	260	787	777	550
input-related indicators	**WU**	**m^3**	10,334	6,205	6,205	10,463	9,205	6,205	9,968	9,700	6,699
	LU	**ha**	1	1	1	1	1	1	1	1	1
	EU	**MJ**	20,832	19,447	16,996	20,103	19,085	18,345	19,957	19,085	18,345

Table 7.7 Environmental impact indicators in selected rice cropping systems of Nam Mae Lao basin – year 2010, results expressed per kg rice produced.

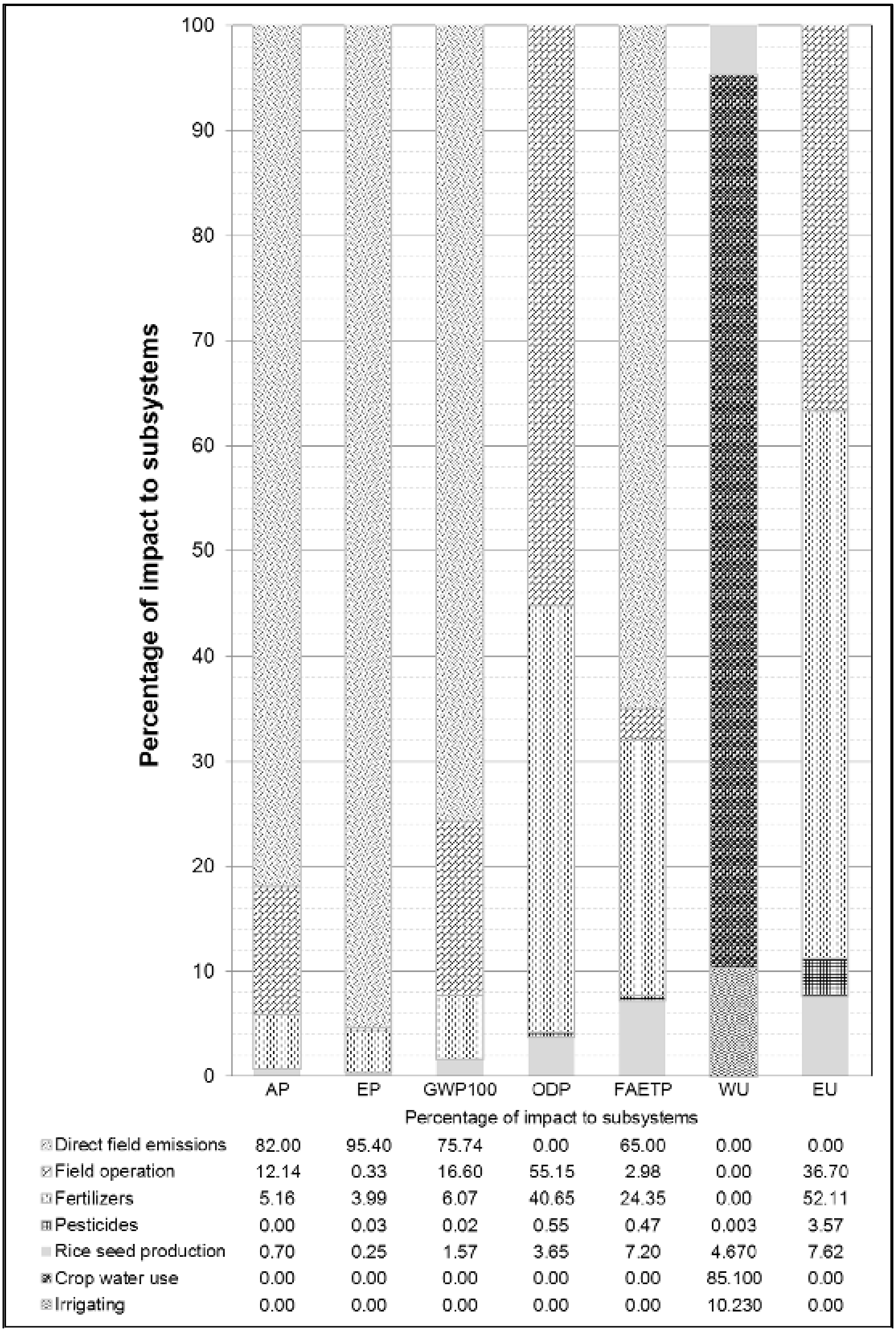
Impact indicator		**Reference unit**	**Rain-fed**			**Wet-season irrigated rice**			**dry-season irrigated rice**		
			Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
			Ref. Unit/1 kg of paddy rice								
Output-related indicators	**GWP_{100}**	**kg CO_2-eq**	2.440	2.235	2.050	3.320	2.900	2.680	2.400	2.150	1.990
	EP	**kg PO_4-eq**	0.080	0.060	0.042	0.059	0.045	0.035	0.063	0.050	0.038
	AP	**kg SO_2-eq**	0.034	0.029	0.025	0.032	0.027	0.024	0.315	0.031	0.029
	ODP	**mg CFC-11-eq**	0.049	0.043	0.030	0.050	0.042	0.038	0.060	0.053	0.048
	FAETP	**kg 1,4-DB eq**	0.145	0.089	0.053	0.153	0.129	0.076	0.250	0.214	0.162
input-related indicators	**WU**	**m^3**	3.164	2.096	1.805	2.986	2.562	1.805	3.104	2.749	1.949
	LU	**ha**	0.00036	0.00031	0.00026	0.00032	0.00028	0.00024	0.00032	0.00029	0.00027
	EU	**MJ**	7.04	5.83	5.36	6.13	5.21	4.73	6.17	5.57	5.02



Percentage of impact to subsystems

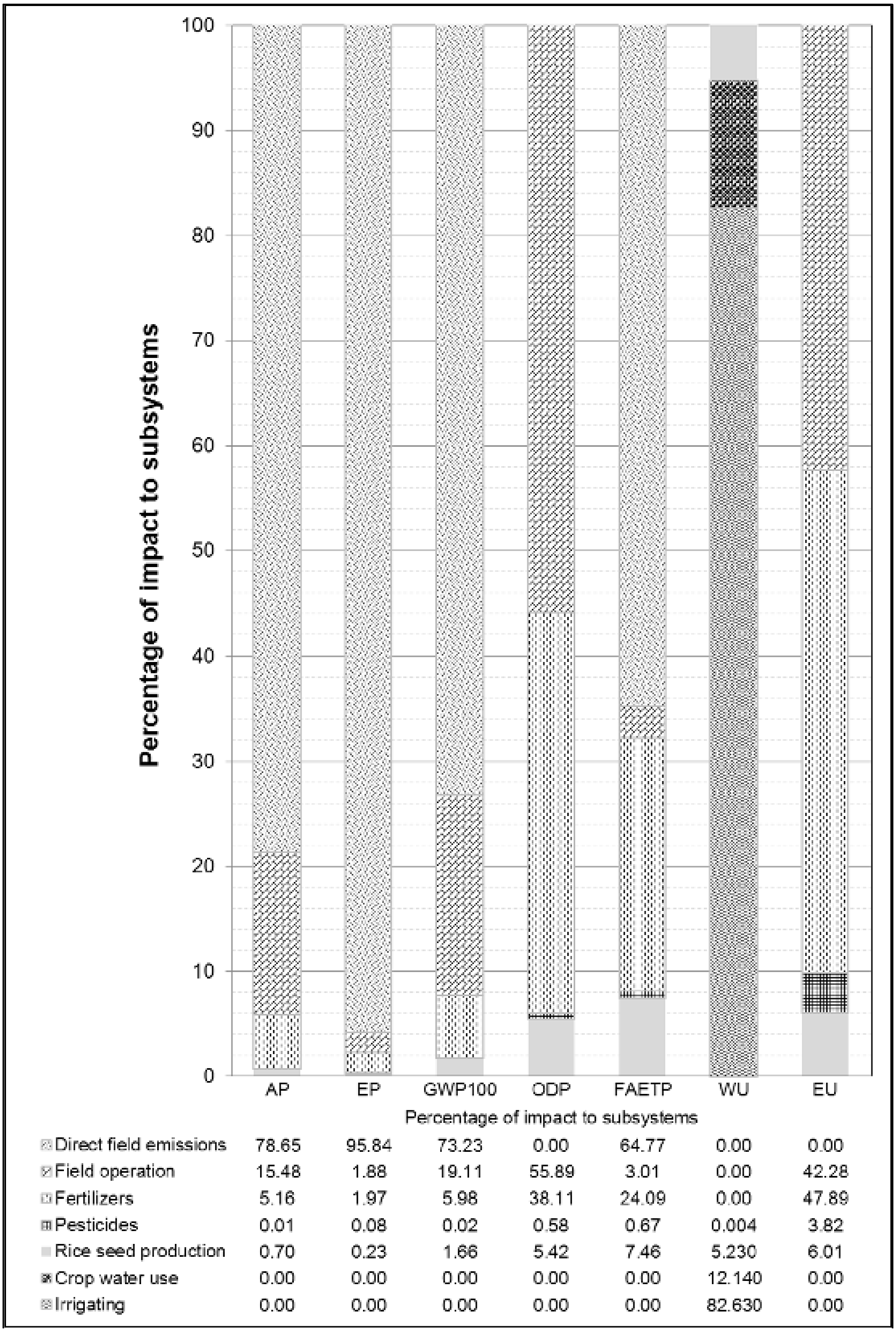
	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	81.00	96.07	65.38	0.00	58.50	0.00	0.00
▨ Field operation	13.10	1.82	25.06	50.16	2.17	0.00	22.01
▨ Fertilizers	5.20	1.88	8.41	46.17	31.52	0.00	65.89
▦ Pesticides	0.00	0.00	0.02	0.43	0.31	0.0038	4.60
■ Rice seed production	0.70	0.23	1.13	3.23	7.50	4.999	7.50
▩ Crop water use	0.00	0.00	0.00	0.00	0.00	94.997	0.00
▨ Irrigating	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 7.1 Contribution of subsystems to the impacts of Rw rice in Nam Mae Lao basin



	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	82.00	95.40	75.74	0.00	65.00	0.00	0.00
▧ Field operation	12.14	0.33	16.60	55.15	2.98	0.00	36.70
⊡ Fertilizers	5.16	3.99	6.07	40.65	24.35	0.00	52.11
⊞ Pesticides	0.00	0.03	0.02	0.55	0.47	0.003	3.57
■ Rice seed production	0.70	0.25	1.57	3.65	7.20	4.670	7.62
⊠ Crop water use	0.00	0.00	0.00	0.00	0.00	85.100	0.00
▩ Irrigating	0.00	0.00	0.00	0.00	0.00	10.230	0.00

Figure 7.2 Contribution of subsystems to the impacts of Iw rice in Nam Mae Lao basin



	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	78.65	95.84	73.23	0.00	64.77	0.00	0.00
▨ Field operation	15.48	1.88	19.11	55.89	3.01	0.00	42.28
▤ Fertilizers	5.16	1.97	5.98	38.11	24.09	0.00	47.89
▦ Pesticides	0.01	0.08	0.02	0.58	0.67	0.004	3.82
■ Rice seed production	0.70	0.23	1.66	5.42	7.46	5.230	6.01
▩ Crop water use	0.00	0.00	0.00	0.00	0.00	12.140	0.00
▩ Irrigating	0.00	0.00	0.00	0.00	0.00	82.630	0.00

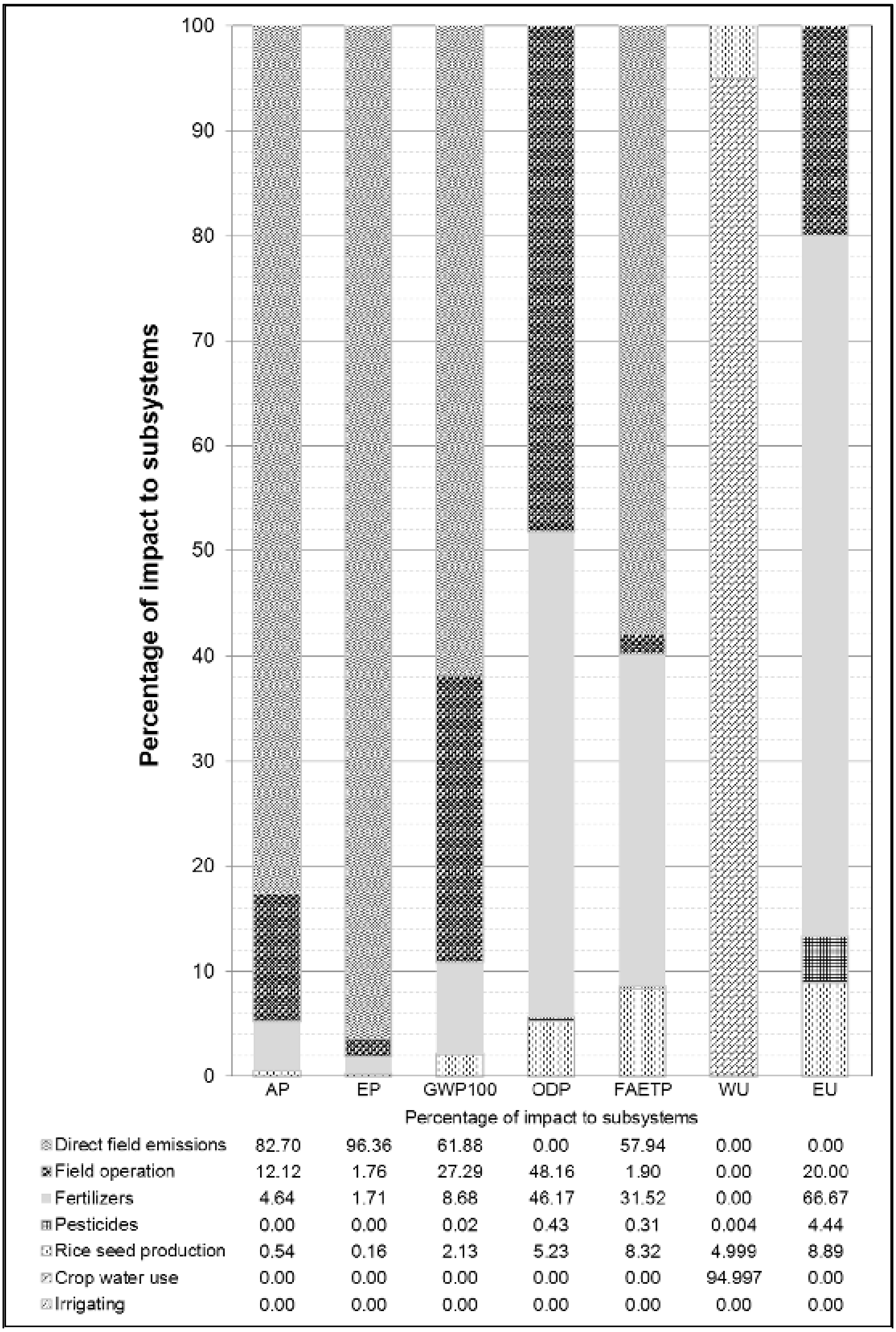
Figure 7.3 Contribution of subsystems to the impacts of Id rice in Nam Mae Lao basin

Table 7.8 Environmental impact indicators in selected rice cropping systems of Lam Sieo Yai basin – year 2010, results expressed per ha cultivated

Impact indicator		Reference unit	Rain-fed			Wet-season irrigated rice			dry-season irrigated rice		
			Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
			Ref. Unit/ha								
Output-related indicators	GWP$_{100}$	kg CO$_2$-eq	8,625	7,054	5,680	15,040	12,784	10,993	15,500	12,141	9,488
	EP	kg PO$_4$-eq	233	178	141	255	208	167	298	217	158
	AP	kg SO$_2$-eq	130	104	83	128	106	88	142	107	80
	ODP	mg CFC-11-eq	210	168	133	214	177	148	240	180	135
	FAETP	kg 1,4-DB eq	818	653	522	952	790	656	1,075	807	606
input-related indicators	WU	m^3	6,305	6,285	6,295	7,053	7,026	7,035	7,256	7,256	7,256
	LU	ha	1	1	1	1	1	1	1	1	1
	EU	MJ	17,464	17,351	17,302	19,810	19,687	19,498	21,076	19,938	18,504

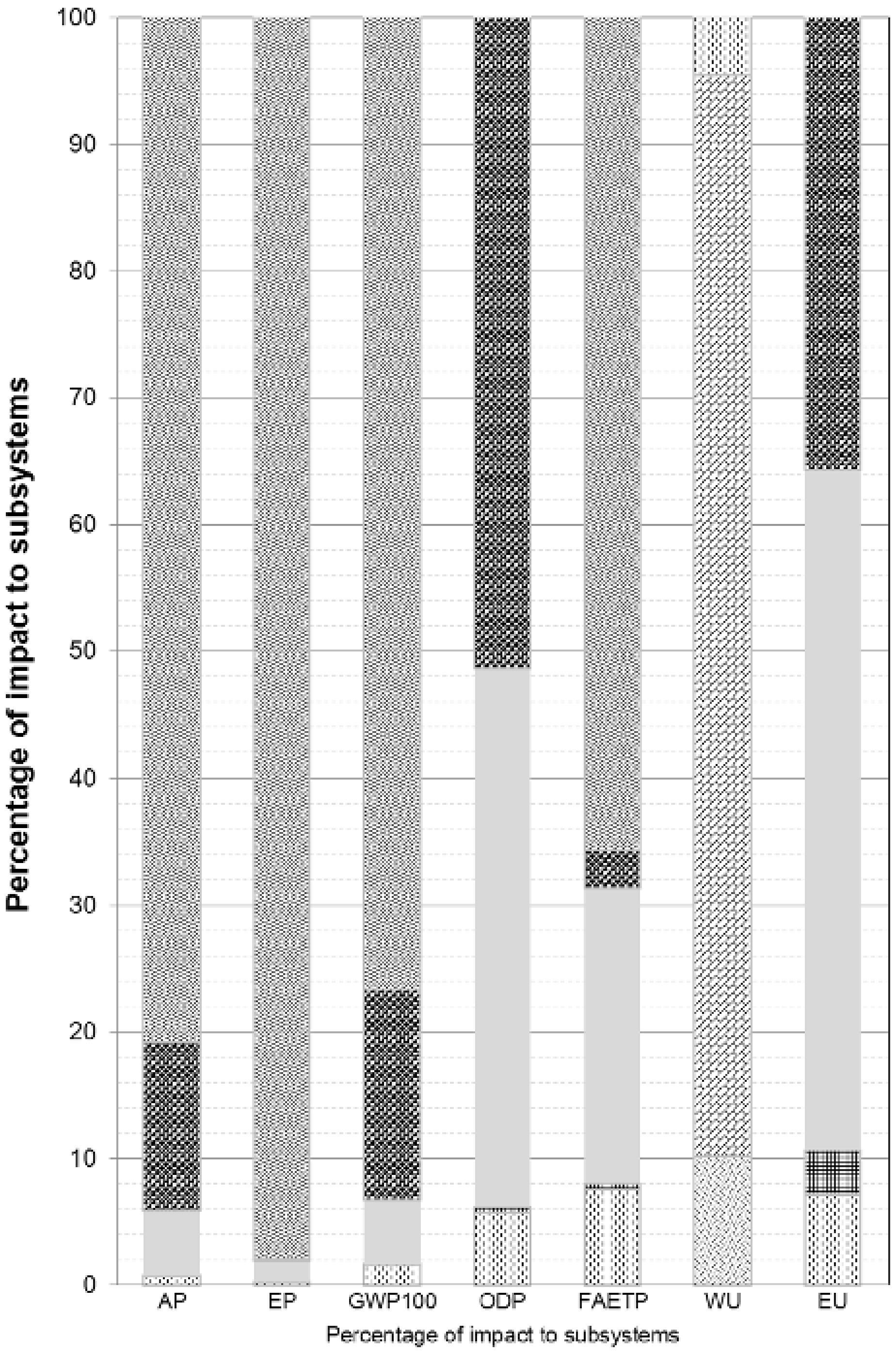
Table 7.9 Environmental impact indicators in selected rice cropping systems of Lam Sieo Yai basin – year 2010, results expressed per kg rice produced.

Impact indicator		Reference unit	Rain-fed			Wet-season irrigated rice			dry-season irrigated rice		
			Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
			Ref. Unit/1 kg of paddy rice								
Output-related indicators	GWP$_{100}$	kg CO$_2$-eq	3.450	2.970	2.840	5.120	4.870	4.510	6.200	5.550	5.060
	EP	kg PO$_4$-eq	0.093	0.075	0.070	0.087	0.079	0.069	0.119	0.099	0.084
	AP	kg SO$_2$-eq	0.052	0.044	0.042	0.044	0.040	0.036	0.057	0.049	0.043
	ODP	mg CFC-11-eq	0.084	0.071	0.067	0.073	0.068	0.061	0.096	0.082	0.072
	FAETP	kg 1,4-DB eq	0.327	0.275	0.261	0.324	0.301	0.269	0.430	0.369	0.323
input-related indicators	WU	m^3	3.153	2.646	2.518	2.886	2.676	2.395	3.870	3.317	2.902
	LU	ha	0.0005	0.00042	0.0004	0.00041	0.00038	0.00034	0.00053	0.00046	0.0004
	EU	MJ	8.73	7.29	6.94	8.13	7.50	6.64	9.87	9.64	7.98



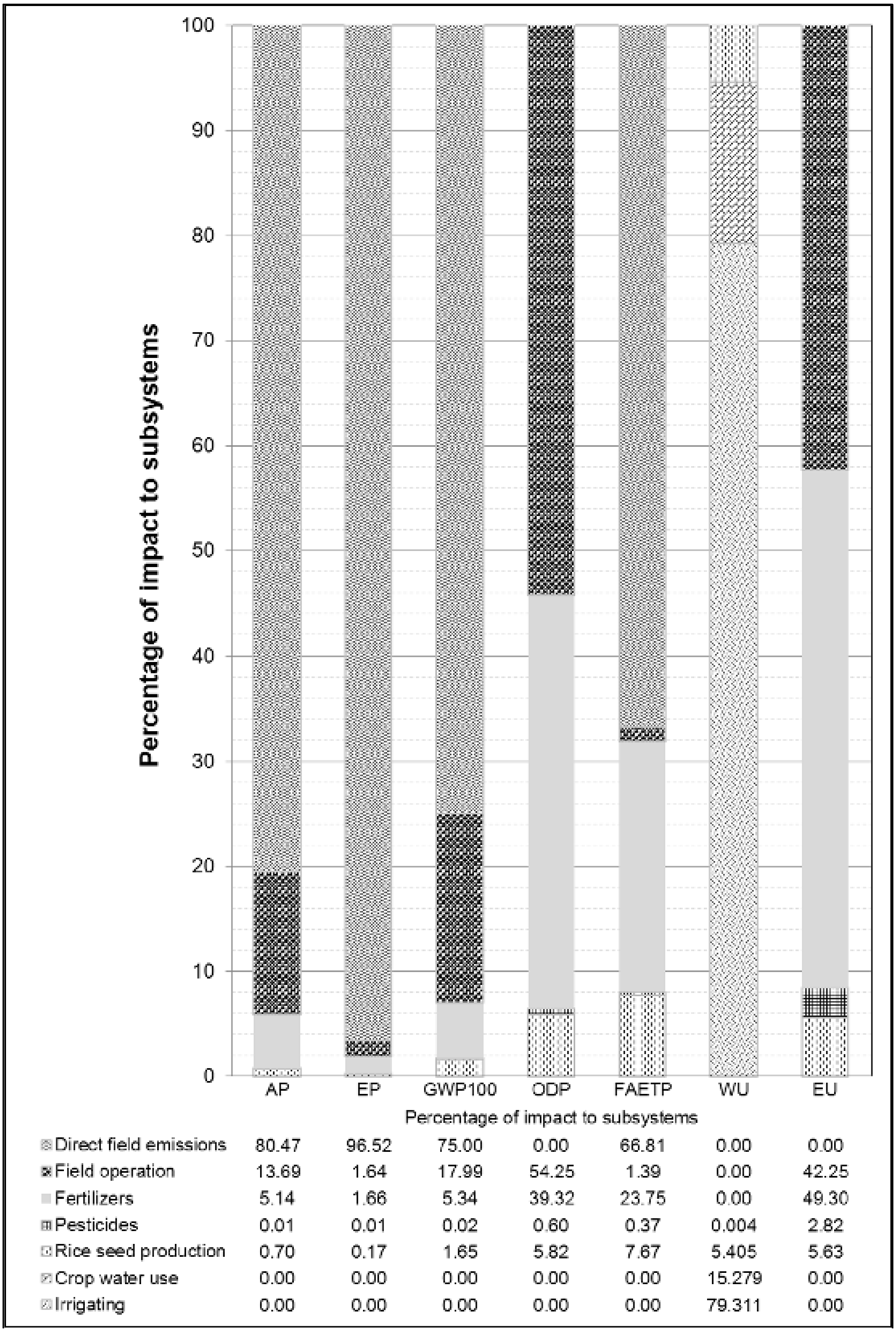
	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	82.70	96.36	61.88	0.00	57.94	0.00	0.00
▩ Field operation	12.12	1.76	27.29	48.16	1.90	0.00	20.00
■ Fertilizers	4.64	1.71	8.68	46.17	31.52	0.00	66.67
⊞ Pesticides	0.00	0.00	0.02	0.43	0.31	0.004	4.44
⊡ Rice seed production	0.54	0.16	2.13	5.23	8.32	4.999	8.89
▧ Crop water use	0.00	0.00	0.00	0.00	0.00	94.997	0.00
▧ Irrigating	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 7.4 Contribution of subsystems to the impacts of Rw rice in Lam Sieo Yai basin



	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	80.79	97.93	76.74	0.00	65.66	0.00	0.00
▩ Field operation	13.35	0.13	16.60	51.35	2.98	0.00	35.71
■ Fertilizers	5.16	1.76	5.07	42.45	23.35	0.00	53.57
⊞ Pesticides	0.00	0.01	0.02	0.55	0.47	0.003	3.57
⊡ Rice seed production	0.70	0.19	1.57	5.65	7.54	4.545	7.14
▧ Crop water use	0.00	0.00	0.00	0.00	0.00	85.393	0.00
▨ Irrigating	0.00	0.00	0.00	0.00	0.00	10.058	0.00

Figure 7.5 Contribution of subsystems to the impacts of Iw rice in Lam Sieo Yai basin



	AP	EP	GWP100	ODP	FAETP	WU	EU
▨ Direct field emissions	80.47	96.52	75.00	0.00	66.81	0.00	0.00
▩ Field operation	13.69	1.64	17.99	54.25	1.39	0.00	42.25
■ Fertilizers	5.14	1.66	5.34	39.32	23.75	0.00	49.30
⊞ Pesticides	0.01	0.01	0.02	0.60	0.37	0.004	2.82
⊡ Rice seed production	0.70	0.17	1.65	5.82	7.67	5.405	5.63
▨ Crop water use	0.00	0.00	0.00	0.00	0.00	15.279	0.00
▨ Irrigating	0.00	0.00	0.00	0.00	0.00	79.311	0.00

Figure 7.6 Contribution of subsystems to the impacts of Id rice in Lam Sieo Yai basin

7.3 Statistical analysis of the environmental impacts

Pair-wise tests on calculated means were carried out with Student T-test to check the significance of differences in environmental impacts between pairs of cropping systems.

Table 7.10 Student's T-test analysis on environmental impacts of both basins

Indicators	***p-value***					
	Nam Mae Lao			**Lam Sieo Yai**		
Data Set	**Rw & Iw**	**Rw & Id**	**Iw & Id**	**Rw & Iw**	**Rw & Id**	**Iw & Id**
GWP	***	**	***	***	***	n.s.
EP	***	n.s.	n.s.	n.s.	**	n.s.
AP	***	n.s.	n.s.	n.s.	n.s.	*
FAETP	***	***	***	n.s.	**	**
WU	*	**	n.s.	n.s.	n.s.	n.s.
LU	***	**	**	***	**	**
EU	***	***	***	n.s.	***	***

n.s. not significantly different ($p>0.1$)
* low significant difference at $p\leq0.1$
** significant difference ($p\leq0.05$)
*** highly significant difference ($p\leq0.01$)

Results show that, in Nam Mae Lao, the most significant differences for all variables are between Rw and Iw systems. Also, EU and FAETP, LU and GWP prove significantly different amongst all systems. In Lam Sieo Yai, environmental impacts are overall more homogenous, as differences are less clearly significant when all 3 systems are considered. However, pair-wise analysis shows that Rw systems perform significantly differently than irrigated systems on GWP, and LU, while Id systems perform significantly differently on EU and FAETP. These are explained mostly by differences in water management and pumping requirements.

7.4 Discussion on environmental impacts of Hom Mali production in both basins

7.4.1 Environmental loads

As discussed earlier, the systems under scrutiny are not highly-c cropping systems in terms of use of agro-chemicals, both qualitatively (few sorts are used) and quantitatively. Indeed, with rare exceptions and some variations, farmers tend to apply moderately pesticides and fertilizers, and to abide by recommendations. In Nam Mae Lao basin (North), farmers do not even apply any insecticide, while brown plant-hopper damaging attacks prompt farmers to use isoprocarb in Lam Sieo Yai basin (Northeast). There, only rainfed systems are immune from golden snails (hence no metaldehyde application). Such limited use of pesticides results in limited environmental loads per area cropped, in terms of potentially impacting emissions from pesticides. Yet, low yields make environmental loads per functional unit (kg rice) still significant.

Overall, CH_4 and other GHG emissions prevail as environmental loads, due to cropping conditions, especially in irrigated systems Iw and Id.

7.4.2 Environmental impacts

Environmental loads were translated into impacts using the CML methods. Five output-related potential impact categories were investigated, namely GWP100, acidification, eutrophication, ozone depletion, ecotoxicity (freshwater). Table 7.11 summarizes the LCIA results.

Table 7.11 Environmental impact indicators in Hom Mali rice cropping systems in selected basins. Results expressed per kg paddy rice at farm gate (median values, year 2010).

Basins	**Cropping systems**	**Impact categories**							
		Output-related indicators					**Input-related indicators**		
		GWP$_{100}$	**EP**	**AP**	**ODP**	**FAETP**	**WU**	**LU**	**EU**
		kgCO$_2$-eq	**kgPO$_4$-eq**	**kgSO$_2$-eq**	**mgCFC-11-eq**	**kg1,4-DB eq**	**m^3**	**ha**	**MJ**
Nam Mae Lao	**Rw**	2.235	**0.060**	0.029	0.043	0.089	2.096	**0.00031**	**5.830**
	Iw	**2.900**	0.045	0.027	0.042	0.129	2.562	0.00028	5.210
	Id	2.150	0.050	**0.031**	**0.053**	**0.214**	**2.749**	0.00029	5.569
Lam Sieo Yai	**Rw**	2.970	0.075	0.044	0.071	0.275	2.646	0.00042	7.285
	Iw	4.870	0.079	0.040	0.068	0.301	2.676	0.00038	7.500
	Id	**5.550**	**0.099**	**0.049**	**0.082**	**0.369**	**3.317**	**0.00046**	**9.635**

Overall, all impacts per kg of paddy rice at farm gate are systematically higher in Id systems in Lam Sieo Yai basin, mostly due to lower yields, and water management practices. This is especially marked for EU (more pumping), LU, GWP (water and straw management).

From environmental impact perspective, ranking of systems is not so clear in the North. Impacts are also higher in Id systems of Nam Mae Lao basin, except for GWP (higher in Iw) and EP (higher in Rw). Also, land and energy requirements are higher in Rw in the North.

The higher GWP$_{100}$ in Iw systems in the North and in Id systems in the Northeast are caused by higher CH$_4$ emissions, as explained earlier: in both basins, irrigated systems are exposed to shorter non-flooded per-season conditions, early incorporation of organic residues, and, in the North, Iw systems are continuously flooded. As shown in literature review section (table 2.1), GWP values range between 1kg (Yossapol et al., 2008), 1.6 kg (Hokazono et al., 2009; Wang et al., 2012), and 2 kg CO$_2$-eq (Hokazono and Hayashi, 2012) per kg of paddy rice at farm gate. Even when including milling stages, results from Kasmaprapruet et al. (2009), Blengini and Busto (2009) and Brodt et al. (2008) show GWP values ranging between 2-3 kg CO$_2$-eq per kg of rice at mill gate.

Overall, our results are consistent with these ranges, except for irrigation systems in Lam Sieo Yai basin, where GWP values double, due to high methane emissions related to flooded conditions at the start of the cropping seasons and to the management of organic residues (straw) as explained in sections 5 and 6. It is important to highlight that, in spite of intermittant flooding conditions in Northeast, high methane emissions are still recorded there.

In addition to the lower yields, the higher GWP results (especially compared to other studies) can be further explained by the use of the CH$_4$ baseline emission value suggested by Yan et al. (2003a) that is higher than the generic one suggested by IPCC (2006) for paddy rice, on account of specific pedoclimatic conditions in Northeast and North region.

Overall, our results for Thai rice were either of similar magnitude yet greater (energy use, GWP, ODP), or much greater (Acidification and Eutrophication potentials) compared to the results from other regions. This trend of LCA results per kg of rice being greater in our case study can globally be explained by rice yields being markedly lower in Thailand as well reflected by the sampled systems.

For water use, our results (2.1-3.32 m^3/kg rice) were much higher than those from Wang et al. (2010) (0.431), yet compatible with those from Blengini and Busto (4.9) (2009). In both basins, water use is systematically higher in dry-season irrigation, although with diversity of practices in farmers' decisions and strategies regarding water supplies (pumping episodes). Id systems require more blue water than other two systems, and in the Northeast, due to poor precipitations, significantly higher water use is observed.

This also leads to higher energy requirements, due to higher pumping needs. Our results on energy use (5.2 to 9.6 MJ per kg of rice) and ODP (0.042-0.082 mg CFC11-eq per kg of rice) were similar to those obtained by Blengini and Busto (2009) on Italian rice in highly mechanized field conditions (8.75 MJ for non-renewable energy use and 0.06 mg CFC11-eq for ODP). The higher EP, LU and EU in Nam Mae Lao basin are only due to yield because there are small differences in the input uses in the Rw systems. There are small variations on EP, AP, ODP, FAETP and LU of all rice cropping systems which are only due to yield.

Conversely, our results for AP (0.027-0.49 kg SO_2-eq) and EP (0.045-0.099 kg PO_4-eq) were much greater than the values found in the literature ranging for AP from 0.00616 kg SO_2-eq for Blengini and Busto (2009) to 0.024 kg SO_2-eq for Wang et al. (2010) and for EP from 0.00678 kg PO_4-eq for Blengini and Busto (2009) to 0.013 kg PO4-eq for Wang et al. (2010).

We may try to explain such discrepancies as follows: these impact categories are mostly affected by field emissions of NH_3, NO_3 to water and P to water. As in the case of CH_4 emissions, specific emissions factors or equations were used to estimate field emissions in our case study using equations from Yan et al. (2003b) for estimating ammonia emissions and a combination of nutrient budgets (N or P) and a precise water balance for the studied systems for N and P to water. The greater AP and EP in our study might therefore reflect more favourable conditions (e.g. higher temperatures) for these emissions compared to other situations. However, the insufficient level of detail and transparency in published LCA studies makes also possible certain discrepancies in the methods used across studies. Harmonised methods and assumptions would be desirable to complete LCA study comparisons across contrasted situations.

7.4.3 Contribution analysis

The contribution analyses in all systems show similar patterns, although total water use in Id systems results mostly from blue water use (irrigation water), while WU in Iw systems results mostly from the green water use (natural stocks and flows).

Direct field emissions to air and water contribute overwhelmingly to AP, EP, GWP_{100} and FAETP. Field operations, meaning operations requiring the use of machinery and equipment (including water pumping, and the manufacturing of all equipment) contribute 20% of all energy use and a large part of ODP. Fertiliser application and manufacturing contribute a majority of total energy use, a large part of ODP, FAETP, and a marginal amount to AP, EP and GWP_{100}, due to the prevailing direct emissions at field level. Indeed, nitrogen fertilisers contribute much to GWP through N_2O direct field emissions. Pesticide application and manufacturing contributes marginally to total energy use. Rice seeds also contribute marginally to FAETP and EU. Pesticide application requires small amounts of water, and the main contributor to WU remains crop water use.

Overall, direct field emissions are contributing a main part of input related impact categories at local and regional scales (AP, EP, FAETP) and on the global scale (GWP); they mostly depend on water management practices for methane emissions, and both agrochemical and water management for other emissions. As stated by Blengini and Busto (2009), this predominant role calls for more reliable and site-specific data.

CHAPTER 8

INTEGRATED WATER USE IN LCA OF RICE

Thailand's climate is mainly tropical, *i.e.*, exhibiting hot and humid conditions throughout the year. However, as shown in previous sections, there are major discrepancies between regions in terms of endowment in water resources, and exposure to dry-season water scarcity. Growing crops consumes water; such consumption has a different impact onto the whole agricultural sector, human use, and ecosystems, depending on whether the area where it happens is exposed to water scarcity or not. In other words, the water deprivation potential of a given water consuming activity depends on the location of such activity; one cubic-meter used somewhere might have more or less impact on water deprivation than the same unit consumed somewhere else.

To evaluate the impact of Hom Mali rice cropping in the two case study basins, the water stress index (WSI) of Pfister *et al.* (2009) was used as the tool to indicate the extent of water scarcity in the two basins. This chapter proposes and implements a method to calculate the water stress index at local level (tertiary and quaternary level), which contrasts with the regional and whole river basin approaches proposed by Pfister et al. (2009) and Gheewala et al. (2014) respectively. Basin-wise WSI led to translating water use by rice cropping into an environmental impact indicator (water deprivation potential), which better reflect the impact onto other sectors and users.

The objective is to ascertain whether the inclusion of water stress conditions at basin level in environmental impact analysis modifies the comparative results in the conditions of Thailand. As seen in previous sections, the two basins that are studied are quite different in terms of endowment with water resources and precipitations. Also, such conditions and differences are not properly reflected by existing WSI references and regional maps proposed and used by Pfister et al. (2009). Recently, Gheewala et al. (2014) calculated WSI for each of the 25 major river basins of Thailand. Our point is not to challenge these approaches, but to pinpoint their limitations when coarse geographic definition and broad generic national data are used. The objective is therefore to also propose a regionalized method for Thailand, based on available, local and accurate data, and which would reflect more accurately basin-level conditions. It has been applied in the two case study basins.

8.1 Analysis of land use of selected basins

8.1.1 Analysis of land use of Lam Sieo Yai basin

Table 8.1 shows the types of land use and their area. The largest area is a paddy field with 56% under irrigated system and 24% under rainfed conditions. Other agricultural crops are under rainfed condition. According to Table 8.1, agricultural crops include rice, cassava and sugarcane. Eucalyptus, rubber tree, mango, cashew, pasture and forest are considered as natural crops which need to consider only annual green water use (WU_g). Miscellaneous use and water bodies are neglected from the calculation of water use. There is no industrial area in Lam Sieo Yai, Therefore, water use of industrial sector can be neglected.

8.1.2 Analysis of land use of Nam Mae Lao basin

Table 8.2shows the types of land use and their area. The highest area is forest area which 72% and followed by mixed field crop-mixed orchard and maize areas. Other agricultural crops are under rainfed condition, except rice. The percentage of the paddy field area is about 4% of the total area which 3% is under irrigated system and 1% is under rainfed condition. According to Table 8.2, agricultural crops include rice, cassava and sugarcane. Rubber tree, tea, mulberry, orange, litchi, mango, tamarind, longan, pasture, mixed field crop-mixed orchards and forests are considered as a natural vegetation cover. Miscellaneous use and Water body are neglected from the calculation of water use. There is no industrial area in Nam Mae Lao basin; therefore, water use of industrial sector can be neglected.

8.2 Calculation of total water use of selected basins

As suggested in chapter 4, total water use was assumed to be the sum of water uses in agricultural, forestry and human sectors. Miscellaneous use and water bodies were neglected from the system.

8.2.1 Calculation of total water use of Lam Sieo Yai basin

Table 8.3 shows the total water requirements of agriculture sector in Lam Sieo Yai basin. The amount of water use is 2,948 Mm^3 per year and the highest of water requirement is from irrigated rice, which is 2,246 Mm^3 per year, about 76% of the total water requirement. For natural crops which are eucalyptus, rubber trees, mango, cashew, pastures, forest represent 5% of the total water use.

As shown in Table 8.1, there are 72.05 km^2 of urban areas and the density of population in Lam Sieo Yai basin is about 166.23 persons per km^2. A human water requirement in this area is 361,272 m^3/year or 0.36 Mm^3/year.

Therefore, the total of water use in this area is 2,948.34 Mm^3/year.

Table 8.1 Land use area of Lam Sieo Yai basin

Type of land use		**Area (m^2)**	**Percentage of the area**	**Systems**
Agricultural areas	Paddy fields	1,572,792,444	56.09	Irrigated
		674,053,904	24.04	Rainfed
	Cassava	101,064,117	3.60	Rainfed
	Sugarcane	12,280,310	0.44	Rainfed
	Eucalyptus	13,704,273	0.49	Rainfed
	Rubber tree	55,600	0.00	Rainfed
	Mango	1,408,093	0.05	Rainfed
	Cashew	147,119	0.01	Rainfed
	Pastures	3,241,324	0.12	Rainfed
Urban areas		119,086,373	4.25	-
Forests		147,604,280	5.26	Rainfed
Miscellaneous use		108,557,268	3.87	-
Water bodies		49,979,125	1.78	-
Total		2,803,974,231	100.00	-

Table 8.2 Land use area of Nam Mae Lao basin

Type of land use		Area (m^2)	Percentage of the area	Systems
Agricultural areas	Paddy fields	80,379,174	3.067	Irrigated
		26,793,058	1.022	Rainfed
	Maize	231,094,484	8.817	Rainfed
	Cassava	752700.4162	0.029	Rainfed
	Tobacco	614002.1406	0.023	Rainfed
	Potato	2071674.781	0.079	Rainfed
	Barley	498213.5781	0.019	Rainfed
	Rubber tree	130,135	0.005	Rainfed
	Tea	1,102,799	0.042	Rainfed
	Mulberry	447,065	0.017	Rainfed
	Orange	662583.9609	0.025	Rainfed
	Litchi	1543862.539	0.059	Rainfed
	Mango	3,408,271	0.130	Rainfed
	Tamarind	54,617	0.002	Rainfed
	Longan	16106760.2	0.615	Rainfed
	Pastures	834,437	0.032	Rainfed
	Mixed field crops-Mixed orchards	277,925,066	10.604	Rainfed
Urban areas		72,045,465	2.749	-
Forests		1,885,985,754	71.960	Rainfed
Miscellaneous use		10,164,213	0.388	-
Water bodies		8,268,295	0.315	-
Total		2,620,882,630	100	-

8.2.2 Calculation of total water use of Nam Mae Lao basin

Table 8.4 shows the total water requirements of agriculture sector in Nam Mae Lao basin. The amount of water use in agriculture sector is 2,659 Mm^3 per year and the highest of water requirement is forested areas which are 2,088 Mm^3 per year, about 78% of the total water requirements.

As shown from Table 8.2, there are 119.09 km^2 of the urban areas and the density of population in Nam Mae Lao basin is about 102.32 persons per km^2. A human water requirement in this area is 134,533 m^3/year or 0.13Mm^3/year.

Therefore, the total of water use in this area is 2,659.57 Mm^3/year.

8.3 Calculation of water stress index (WSI)

Table 8.5 shows the calculation of all parameters and WSI of both selected basins by using Pfister et al. (2009) method. At selected basin water stress index value is 1.00 in Lam Sieo

Yai basin and 0.86 in Nam Mae Lao basin when including green water to total water use. Green water is excluded from total water use, WSIs are 0.42 in Lam Sieo Yai basin and 0.01 in Nam Mae Lao basin. WSI of Lam Sieo Yai basin is higher because of higher water use and lower annually available water.

Gheewala et al. (2014) calculated WSI based on average annual rainfall (and excluding green water) for the Kok and Mun river systems, which encompass the Nam Mae Lao and Lam Sieo Yai basins respectively. WSI is 0.018 in Kok river basin, which refers to low water stress; such figure corresponds to our results for WSI in Nam Mae Lao sub-basin. WSI is 0.927 in Mun river basin, which refers to extremely severe water stress; our own calculations in Lam Sieo Yai sub-basin refers to moderate stress conditions (0.42), mostly because our sub-basin is situated in the northern part of the Mun basin, with significantly more rainfall than the rest of it. Our results concur overall with these findings at whole river basin level, yet they arguably provide more accuracy at the local level.

Using equation 2.7, the characterization factor of freshwater depletion in case of including green water use is 0.058 and 0.322 for Nam Mae Lao and Lam Sieo Yai basins, respectively. Freshwater depletion of Nam Mae Lao and Lam Sieo Yai basins are 155.582 and 718.241 Mm^3 per year, respectively. When excluding green water use, no freshwater depletion on the selected basins is observed, that concurs with results reported by Pfister et al. (2009).

As mentioned in chapter 2 (literature review) and 4 (methodology), WSI is used as the characterization factor to calculate water deprivation potential by multiplication of blue water with WSI.

8.4 Water deprivation impact potential from rice production

The water stress index (WSI) of two selected basins are applied as the LCA characterization factors to determine the water deprivation potential, i.e. the amount of water taken away from downstream human users and ecosystems, by water consumption of rice production. To calculate this indicator, blue water consumption for rice production in selected basins were multiplied with WSI of that basin and measured in m^3 water-equivalents (m^3 eq). Pfister et al. (2009) focused on blue water use, and assumed that green water consumption does not change, as a function of the activities assessed in LCA. However, this is a simplification, as paddy rice cropping arguably evaporates more green water than any other common crops. While Pfister recommended that related effects of potential changes in green water flows may be addressed in future research, we decided to calculate WSI with both approaches, i.e. based on blue water use alone, and together with green water use.

The higher WSI found in Lam Sieo Yai basin leads to a higher potential for water deprivation by any water use, compared to Nam Mae Lao basin. Table 8.6 and Table 8.7 show the water deprivation potentials from consumptive water use to produce 1 kg of paddy rice in Nam Mae Lao and Lam Sieo Yai basins, respectively.

On a product mass basis (kg of paddy produced at farm gate), blue water use figures for rice production in dry season are similar between the two basins (approximately 2.5 m^3/kg). Yet, when a water deprivation potential is computed, such consumptions translate into a negligible amount in Nam Mae Lao basin (North), and into significant water deprivation in

Lam Sieo Yai basin (North East), as shown in tables 8.6 and 8.7. Should calculations be done with inclusion of green water, results would only show an even more acute water deprivation, with the same trend (more acute in the North East).

Such results demonstrate the relevance of discriminating basins on a WSI basis, resulting in possible changes in quantification and ranking of products (from LCA environmental impact basis) when severe water scarcity conditions are factored in. The two basins under scrutiny were interesting for such analysis since they show contrasted hydrological and climatic conditions.

Also, the case study highlights the need to use as regional as possible data, based upon secondary or tertiary river basin level when possible, rather than national maps or references. Finally, LCA's water deprivation potential, as an impact indicator, provides information that product water footprint cannot reveal, with regards to production location and the water scarcity conditions thereof.

Rice is a high water-consuming crop. Water consumption presents an additional important ecological dimension that needs to be considered to provide a more complete basis for environmental decision making, to avoid burden shifting.

Table 8.3 Total water requirement of agriculture sector in Lam Sieo Yai basin

Crop	Area (ha)	System	Duration	Total WU_g (m^3/ha)	Total WU_b (m^3/ha)	Total Water use (m^3/ha)	Total Water use (m^3)	Total Water use (Mm^3)
Rice	67,405	Rainfed	Jun - Oct	6,285	0.25	6,285	423,659,730	423.66
	157,279	Irrigated	Jan - May	1,172	6,084	7,256	1,141,218,197	1,141
			Jun - Oct	6,285	741	7,026	1,105,043,971	1,105
Cassava	10,106	Rainfed	Jan - Jun	3,976	0	3,976	40,183,093	40.18
		Rainfed	July - Dec	6,006	0	6,006	60,699,109	60.70
Sugarcane	1,228	Rainfed	July - June	8,574	0	8,574	10,529,138	10.53
Eucalyptus	1,370	Rainfed	Jan - Dec	10,029	0	10,029	13,744,015	13.74
Para rubber	6	Rainfed	Jan - Dec	10,029	0	10,029	55,761	0.06
Mango	141	Rainfed	Jan - Dec	10,029	0	10,029	1,412,177	1.41
Cashew	15	Rainfed	Jan - Dec	10,029	0	10,029	147,545	0.15
Pasture	324	Rainfed	Jan - Dec	10,029	0	10,029	3,250,724	3.25
Forest	14,760	Rainfed	Jan - Dec	10,029	0	10,029	148,032,333	148.03
Total							2,947,975,793	2,948

Table 8.4 Total water requirement of agriculture sector in Nam Mae Lao basin

Crop	**Area (ha)**	**System**	**Duration**	**Total WU_g (m^3/ha)**	**Total WU_b (m^3/ha)**	**Total Water use (m^3/ha)**	**Total Water use (m^3)**	**Total Water use (Mm^3)**
Rice	8,038	Rainfed	Jun - Oct	6,205	0.46	6,205	49,878,975	49.88
	2,679	Irrigated	Jan - May	2,729	6,970	9,699	25,986,587	25.99
			Jun - Oct	6,205	3,001	9,206	24,665,689	24.67
Maize	23,109	Rainfed	Jun - Nov	5,802	0	5,802	134,081,020	134.08
Cassava	75	Rainfed	Jan - Jun	3976	0	3,976	299,274	0.30
			July - Dec	7003	0	7,003	527,116	0.53
Tobacco	61	Rainfed	July - Oct	5370	0	5,370	329,719	0.33
Potato	207	Rainfed	July - Nov	6087	0	6,087	1,261,028	1.26
Barley	50	Rainfed	July - Oct	5764	0	5,764	287,170	0.29
Para rubber	13	Rainfed	Jan - Dec	11,069	0	11,069	144,047	0.14
tea	110	Rainfed	Jan - Dec	11,069	0	11,069	1,220,688	1.22
Mulberry	45	Rainfed	Jan - Dec	11,069	0	11,069	494,856	0.49
Orange	66	Rainfed	Jan - Dec	11,069	0	11,069	733,414	0.73
Litchi	154	Rainfed	Jan - Dec	11,069	0	11,069	1,708,901	1.71
Mango	341	Rainfed	Jan - Dec	11,069	0	11,069	3,772,615	3.77
Tamarind	5	Rainfed	Jan - Dec	11,069	0	11,069	60,455	0.06
Longan	1,611	Rainfed	Jan - Dec	11,069	0	11,069	17,828,573	17.83
Pasture	83	Rainfed	Jan - Dec	11,069	0	11,069	923,638	0.92
Mixed field crop-Mixed orchard	27,793	Rainfed	Jan - Dec	11,069	0	11,069	307,635,255	307.64
Forest	188,599	Rainfed	Jan - Dec	11,069	0	11,069	2,087,597,631	2,088
Total							2,659,436,653	2,659

Table 8.5 Calculation of water stress index and freshwater depletion of selected basins

Parameters	**Unit**	**Nam Mae Lao basin**		**Lam Sieo Yai basin**	
		Including WUg	**Excluding WUg**	**Including WUg**	**Excluding WUg**
Annual rainfall	mm	1,641	1,641	886	886
Total Area (A)	km^2	2,621	2,621	2,804	2,804
Annually available water in basin (WA = Annual rainfall x A)	Mm^3	4,301	4,301	2,483	2,483
Total water use (WU)	Mm^3	2,660	51	2,230	963
WTA is WU/WA	m^3/m^3	0.62	0.01	0.90	0.39
Standard deviation of monthly rainfall (S*month)	-	123.32	123.32	130.84	130.84
(S*month)^2	-	15,208	15,208	17,120	17,120
Standard deviation of annual rainfall (S*year)	-	274.20	274.20	266.30	266.30
(S*year)^2	-	75,183	75,183	70,914	70,914
Aggregated measure of dispersion of rainfall (VF)	-	2.95	2.95	2.70	2.70
Strongly regulated flow (SRF) Condition	-	SRF	SRF	SRF	SRF
Modified WTA (WTA*)	Mm^3	1.06	0.02	1.48	0.64
Water stress index (WSI)	-	0.860	0.010	1.000	0.420
characterization factor for the midpoint indicator “freshwater depletion” ($F_{depletion}$)	-	0.058	0	0.322	0
Freshwater depletion	Mm^3	155.582	0	718.241	0

Table 8.6 Water deprivation potential of rice production in Nam Mae Lao basin

Indicator	**Reference Unit**	**Rain-fed**			**Wet-season irrigated rice**			**dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		Reference unit/kg of paddy rice								
Blue water use	**m^3**	1.01	6.39E-04	4.04E-04	1.00	8.47E-01	3.59E-04	2.68	2.26	1.41
Water deprivation potential	**m^3 eq**	0.01	6.39E-06	4.04E-06	0.01	8.47E-03	3.59E-06	0.03	0.02	0.01

Table 8.7 Water deprivation potential of rice production in Lam Sieo Yai basin

Indicator	**Reference Unit**	**Rain-fed**			**Wet-season irrigated rice**			**dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		Reference unit/kg of paddy rice								
Blue water use	**m^3**	0.19	1.44E-04	1.05E-04	0.16	9.10E-05	8.01E-05	2.88	2.48	2.46
Water deprivation potential	**m^3 eq**	0.08	6.06E-05	4.42E-05	0.07	3.82E-05	3.36E-05	1.21	1.04	0.08

CHAPTER 9

EFFICIENCY ANALYSES

This chapter investigates jointly the environmental, technical and economic performances of rice cropping systems in Nam Mae Lao and Lam Sieo Yai Basins as an attempt to quantify the sustainability level of rice farming, and to reveal options and areas for improvements. The results of techno-economic analysis were used for calculation of eco-efficiency and results of techno-economic and LCA results were used for analysis of technical efficiency and environmental efficiency of different rice cropping systems in order to ascertain the relationships between these efficiencies and rice cropping systems (rainfed, wet-season irrigated and dry-season irrigated rice). The set of indicators was computed from primary data, to reflect technical efficiency and eco-efficiency by using Data Envelopment Analysis (DEA) technique.

9.1 Eco-Efficiency and net return to environmental impact of selected basins

According to WBCSD (2000), eco-efficiency is represented by the ratio “Product or service value/Environmental influence” In this study, market value (baht/1 kg of paddy Hom Mali rice) was selected as the product value and global warming potential (GWP_{100}), eutrophication (EP), acidification (AP), ozone depletion (ODP), freshwater aquatic ecotoxicity (FAETP) and water use (WU), land use (LU) and energy use (EU) were selected as the environmental influence or environmental impact. It means that the high value of eco-efficiency can refer to high sustainable practice. Table 9.1 and Table 9.3 report the eco-efficiency of the three systems as per impact category in both selected basins. Because the market price (the market value at farm gate) of paddy rice was identical in all three systems (12 THB per kg in 2010), the results are basically reversed values of the results on impact per kg of rice produced are shown in Table 7.7 and Table 7.9. However, there is an interest in reporting eco-efficiency as such, as it represents how cropping systems generate a total value per environmental impact unit they create.

In that sense, according to Table 9.1, it can be observed that the rice cropping systems under wet-season irrigated condition in Nam Mae Lao basin are more eco-efficient than others, with the exception of GWP_{100}, FAETP and WU impacts, which Rw systems perform slightly better on FAETP and WU and Id systems lag significantly behind the other two systems, except GWP_{100}. Therefore, it can be concluded that irrigated rice cropping systems during the dry season provides the lowest eco-efficiency on the overall impact indicators. Conversely, wet-season irrigated systems in Nam Mae Lao basin prove more eco-efficient than others.

Table 9.2 reports the net return on the environmental impact, that is, the net income left to farmers per environmental impact unit. It represents how cropping systems generate income for the farmers per environmental impact they create. The results show that Iw systems provide the highest net return per impact, except for GWP_{100} (Id systems perform better), and FAETP (Rw systems perform better). Irrigated rice cropping systems during dry season shows the lowest eco-efficiency on the overall impact indication except for GWP_{100} when compared with other rice cropping systems.

The eco-efficiency ranking in Lam Sieo Yai is radically different. As shown in Table 9.3, Rw systems in Lam Sieo Yai basin are more eco-efficient than others, with the exception of AP, ODP and LU impacts, for which Iw systems perform slightly better. Id systems still lag significantly behind the other two systems. Overall, irrigated systems are less eco-efficient than rainfed systems in that basin.

Table 9.4 shows that Iw systems provide more net return per impact than others, with the notable exception of GWP_{100} and FAETP for which Rw still performs better. Id systems still lag far behind the other systems in terms of net return efficiency. This shows that considering net income slightly irons out the differences; yet Id systems are confirmed as the lowest eco-efficient hierarchy

Interestingly, in Nam Mae Lao basin, Iw systems value each ton of CO_2-eq emitted at 5,581 THB, or approximately 194 US$ per ton. Id and Rw systems value each ton of CO2-eq emitted at 178 and 137 US$, respectively. In Lam Sieo Yai basin, Rw systems value each ton of CO_2-eq emitted at 4,040 THB, or approximately 134 US$ per ton. Iw and Id systems value each ton of CO_2-eq emitted at 82 and 72 US$, respectively (from tables 9.1 and 9.3). These values far exceed the trading price of CO_2 set up by the European Union Emissions Trading Scheme, the first international emission allowance trading system established after the Kyoto protocol, which price is the highest compared to other national systems, and ranged between 16 and 20 US$ throughout 2010.

The maximum, median and median of Eco-efficiency (gross income per environmental impact, as per category) are Net income per environmental impact (as per category) of both selected basins are shown in APPENDIX D.

Overall, the results on eco-efficiency strikingly concur with results on techno-economic performances: wet season irrigated systems in the North are also the most eco-efficient, and rainfed systems in the Northeast are the most eco-efficient. However, conversely to techno-economic analysis, eco-efficiency analysis highlights that Id systems are, in both basins, the least eco-efficient systems of all.

Table 9.1 Eco-efficiency (gross income per environmental impact, as per category) of Nam Mae Lao basin – year 2010

Impact indicator	**Reference unit**	**Eco-Efficiency**		
		Rw	**Iw**	**Id**
		Baht/Ref. Unit		
GWP_{100}	**kg CO_2-eq**	5.4	4.1	5.6
EP	**kg PO_4-eq**	199.9	264.3	238.0
AP	**kg SO_2-eq**	407.5	438.8	389.6
ODP	**mg CFC-11-eq**	276.5	285.4	228.4
FAETP	**kg 1,4-DB eq**	134.2	93.4	56.1
WU	**m^3**	5.7	4.7	4.4
LU	**ha**	39,094	43,125	41,250
EU	**MJ**	2.1	2.3	2.2

Table 9.2 Net income per environmental impact (as per category) of Nam Mae Lao basin – year 2010

Impact indicator	**Reference unit**	**Net income return to environmental impact**		
		Rw	**Iw**	**Id**
		Baht/Ref. Unit		
GWP_{100}	**kg CO_2-eq**	2.3	2.0	2.6
EP	**kg PO_4-eq**	84.8	127.5	103.7
AP	**kg SO_2-eq**	175.7	216.1	174.9
ODP	**mg CFC-11-eq**	119.7	137.7	105.9
FAETP	**kg 1,4-DB eq**	50.9	45.0	26.6
WU	**m3**	2.2	2.4	2.1
LU	**Ha**	16,944	21,355	18,086
EU	**MJ**	0.9	1.1	1.0

Table 9.3 Eco-efficiency (gross income per environmental impact, as per category) of Lam Sieo Yai basin – year 2010

Impact indicator	**Reference unit**	**Eco-Efficiency**		
		Rw	**Iw**	**Id**
		Baht/Ref. Unit		
GWP_{100}	**kg CO_2-eq**	4.0	2.5	2.2
EP	**kg PO_4-eq**	159.8	151.7	121.1
AP	**kg SO_2-eq**	275.2	297.0	246.4
ODP	**mg CFC-11-eq**	170.0	177.5	146.2
FAETP	**kg 1,4-DB eq**	43.6	39.9	32.5
WU	**m3**	4.5	4.5	3.6
LU	**ha**	28,500	31,500	26,250
EU	**MJ**	1.6	1.6	1.3

Table 9.4 Net income per environmental impact (as per category) of Lam Sieo Yai basin – year 2010

Impact indicator	**Reference unit**	**Net return to environmental impacts**		
		Rw	**Iw**	**Id**
		Baht/Ref. Unit		
GWP_{100}	**kg CO_2-eq**	1.4	0.9	0.4
EP	**kg PO_4-eq**	53.7	55.6	24.6
AP	**kg SO_2-eq**	91.5	109.7	49.7
ODP	**mg CFC-11-eq**	56.7	64.5	29.7
FAETP	**kg 1,4-DB eq**	14.6	14.5	6.6
WU	**m3**	1.5	1.6	0.7
LU	**Ha**	9,588	11,550	5,291
EU	**MJ**	0.56	0.59	0.3

9.2 Efficiency analyses by the combination of techno-economic analysis, LCA and DEA approaches

As mentioned in methodology chapter (Table 4.25), a number of variables were used to assess the technical and environmental efficiencies of each rice cropping system based upon Data Envelopment Analysis.

All the data used in this section were computed based on the 60 DMUs per basin, and shown in chapters 6 (techno-economic performances), and 7 (environmental impacts). Data may be found in table 6.1, 6.3, 7.6, 7.8 and appendix E.

9.2.1 Technical efficiency analysis of selected basins

Table 9.5 presents the results of the efficiency analysis (efficiency scores) according to constant return to scale (CRS), variable return to scale (VRS) and scale efficiency (SE) methods.

VRS method results in high technical efficiency (TE_{VRS} > 90%) in all systems. In both basins, Rw systems perform very high with median scores TE_{VRS} of 99.85% and 100% in Nam Mae Lao and Lam Sieo Yai basins, respectively. This indicates that Rw systems make relatively better use of inputs and resources than other two rice cropping systems. Differences are not marked between systems, due to the wide homogeneity of technical practices and performances, which was already highlighted in chapter 6.

CRS method provides slightly more contrasted results, with lower efficiency scores overall. In the Nam Mae Lao basin the highest technical efficiency is observed in irrigated systems (Iw then Id); Rw systems come third. In the Lam Sieo Yai basin, wet season systems perform far better (Rw and Iw have very close scores), while Id systems are lagging far behind.

SE scores converge with CRS based scores and confirm that in the North, it is the water management system that determines technical efficiency; irrigated systems perform better than rainfed ones. In the North East, it is the season (and water scarcity) that determines technical efficiency; Rw and Iw systems are close and perform far better than Id systems. Of all systems studied, Id systems in Lam Sieo Yai basin show particularly low scale efficiency scores, which indicate that they perform at increasing return to scale, indicating that they are far from optimizing the return to input use, with sub-optimal use of most inputs. Low SE scores usually indicate that DMUs perform at increasing return to scale, and are still far from optimal use (small or no return to scale) of production factors; also overarching limiting factors may hinder the optimal expression of inputs. In the case of Id systems, limited water supply may lead to sub-optimal irrigation, which in turn may explain why other inputs (e.g. fertilization) cannot play their role. In spite of high input supply, as shown in chapter 6, Id systems in the North East are not performing properly. These results are confirmed further by frequency analysis of TE scores in Table 9.5.

More detailed results of technical efficiency analysis in both basins are shown in Appendix E.

Table 9.5 TE analysis, as per rice cropping systems of both basins

Basins	Efficiency	Rainfed rice			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	**Median**	**min.**	**Max.**	**Median**	**min.**	**Max.**	**Median**	**min.**
Nam Mae Lao	TE_{VRS}[a]	1	.999	.954	1	.987	.948	1	.955	.915
	TE_{CRS}[b]	1	.693	.403	1	.861	.618	.989	.722	.572
	SE[c]	1	.698	.403	1	.883	.651	.989	.766	.604
Lam Sieo Yai	TE_{VRS}[a]	1	1	1	1	.971	.952	1	.942	.926
	TE_{CRS}[b]	1	.795	.463	1	.769	.606	.670	.377	.173
	SE[c]	1	.795	.463	1	.790	.636	.697	.404	.184

[a] Technical efficiency by VRS, [b] Technical efficiency by CRS, [c] Scale efficiency

9.2.2 Environmental efficiency analysis of selected basins

Table 9.6 presents the results of the environmental efficiency analysis in both selected basins with DEA using CRS, VRS and SE methods.

In both regions, EE_{VRS} scores are high (>90%) for all systems, although of rice cropping systems under rainfed (Rw) are the highest environmental efficiencies in both basins. In the North, Iw systems are very close to Rw ones with high EE_{VRS} while Id systems are behind. In the Northeast, the hierarchy is clearer, with Rw systems more environmentally efficient that irrigated systems.

The CRS method provides similar results, although it allows for clearer discrimination of systems, as in the case of technical efficiency. Rw systems are more environmentally efficient and Id systems are the least efficient in both basins. Overall, median EE scores are very high, which indicate that most systems perform soundly in terms of environment. The only systems that show significantly lower scores are Id systems in the North East.

The EE scores provided by SE method confirm the CRS based ones, with same hierarchy and differences between systems, except in the North East, where Iw systems overcome Rw systems with slightly higher scale efficiency. These results are confirmed further by frequency analysis of TE scores in Table 9.5.

Overall, environmental efficiency analysis of rice systems, based on DEA scores, demonstrate the relatively high EE of all systems, compared to more contrasted TE. Also, Rw systems perform extremely well, and Id systems are least environmentally efficient everywhere. Such results complement interestingly the ones on TE. In the North East, there is a confirmation from the environmental perspective that Id systems are really poorly performing, which was already clear from technical efficiency viewpoint. In the North, further analysis and trade-offs are required to complete the assessment since Rw systems are more environmental friendly (while all systems still perform reasonably well) but they are the least efficient technically.

Table 9.6 Environmental efficiency analysis, as per rice cropping systems of selected basins

Basins	Efficiency	Rainfed rice			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	min.	Max.	Median	min.	Max.	Median	min.
Nam Mae Lao	EE_{VRS}[a]	1	1	.949	1	1	.937	1	.991	.924
	EE_{CRS}[b]	1	.986	.852	1	.966	.837	1	.945	.760
	SCE[c]	1	.986	.852	1	.976	.859	1	.965	.760
Lam Sieo Yai	EE_{VRS}[a]	1	1	.998	1	.896	.894	1	.869	.866
	EE_{CRS}[b]	1	.803	.642	.976	.799	.700	1	.670	.521
	SCE[c]	1	.803	.642	1	.891	.782	1	.771	.602

[a] Environmental efficiency by VRS, [b] Environmental efficiency by CRS, [c] Scale efficiency

9.3 Sustainability analysis: the identification of the most sustainable systems

The sustainability of a given production system may be considered as its ability to combine successfully the three typical dimensions: techno-economic performance (viability), environmental innocuousness (reproducibility), and social acceptability (livability) (Landais, 2002). In this research, it has been possible to approach the two former.

9.3.1 Comparing systems' performances

We first identified and compared the best 10% systems (as sub-groups or deciles) which showed highest net income, lowest production costs, and lowest environmental impacts, respectively. Table 9.7 and Table 9.8 show the results.

Results strikingly reveal that, in both basins, none of the systems with the highest net income are among the ones with any lower environmental impact. Also, none of the systems with the lowest production costs are among the ones with highest net income. Some of the systems with lowest production costs are found in the deciles with low environmental impact.

Interestingly, the decile with lowest production costs does not include systems that use transplanting in both basins (probably due to high labor costs incurred by this method). In Nam Mae Lao basin, dry-seed seedling is systematically associated with lowest acidification, toxicity and water deprivation potentials.

Overall, these results reveal that high net income seems incompatible with low environmental impacts. There seem to be a trade-off between both types of performance. Also, high net income is not linked to low production costs, while the latter has connections with low impacts. It does not seem possible to achieve high yields at high production costs and simultaneously to have low impacts.

As a consequence, attempts to improve the sustainability of Hom Mali rice systems in both basins will also require compromise and trade-offs. Reduction in input and resource use, while sustaining yields seems to be the way forward, which requires increased efficiency of those inputs and resources.

Table 9.7 Deciles of best performing rice systems in Nam Mae Lao Basin

Higher net income	Lower total cost	Lower GWP	Lower EP	Lower AP	Lower FAETP	Lower WDP	Lower Fossil EU
36 DSw	13 Dsd	45 Dsd	40 T	11 Dsd	13 Dsd	22 Dsd	28 DSw
37 DSw	31 DSw	41 Dsd	39 T	13 Dsd	11 Dsd	21 Dsd	27 DSw
38 T	51 DSw	42 Dsd	60 T	10 Dsd	1 Dsd	5 Dsd	32 DSw
18 T	11 Dsd	1 Dsd	31 Dsw	1 Dsd	5 Dsd	10 Dsd	11 Dsd
23 DSw	29 DSw	5 Dsd	59 T	5 Dsd	14 Dsd	4 Dsd	3 Dsd
16 T	30 DSw	14 Dsd	51 Dsw	14 Dsd	10 Dsd	6 Dsd	29 DSw

▒ Rainfed rice system
□ Wet season irrigated rice system
▓ dry season irrigated rice system
Dsw is a direct wet seeding method
Dsd is adirect dry seeding method
T is a transplanting method

Table 9.8 Deciles of best performing rice systems in Lam Sieo Yai Basin

10% higher net income	10% lower total cost	10% lower GWP	10% lower EP	10 % lower AP	10% lower FAETP	10% lower WDP	10% lower Fossil EU
36 T	48 Dsd	16 T	18 T	58 T	16 T	19 Dsw	6 Dsw
38 T	6 Dsd	18 T	16 T	16 T	18 T	20 Dsw	9 Dsw
37 T	10 Dsd	17 T	58 T	18 T	20 T	1 Dsd	16 T
40 Dsw	13 Dsd	19 Dsw	17 T	59 T	19 Dsw	2 Dsd	18 T
39 Dsw	17 Dsw	20 Dsw	20 Dsw	60 T	17 Dsw	3 Dsd	10 Dsw
29 Dsd	3 Dsd	10 Dsd	19 T	36 T	58 T	4 Dsd	8 Dsw

▒ Rainfed rice system
□ Wet season irrigated rice system
▓ dry season irrigated rice system
Dsw is a direct wet seeding method
Dsd is a direct dry seeding method
T is a transplanting method

9.3.2 Comparing systems' efficiencies

Following preliminary results on comparative performances, we focused on comparing technical and environmental efficiencies, as both are closer to sustainability indicators than performances, as they include elements of trade-off. It is assumed that among the rice systems that were studied, those with the highest technical efficiency (those that mobilize the most efficiently inputs and resources to maximize rice production) and the highest environmental efficiency (those that minimize adverse environmental effects while maximizing rice production) are the most sustainable.

Under such assumption, we sorted out the two sub-groups according to individual efficiency scores (>90%). Only scores generated by CRS method were used, since it is the approach that best discriminate DMUs, and CRS scores are well aligned with SE scores, as shown previously.

According to the results in Nam Mae Lao basin (see appendix E), the highest TE_{CRS} are generated by DMUs numbered 13, 17, 31, 36, 37. The highest EE_{CRS} are achieved by DMUs numbered 4, 6, 10, 11, 12, 13, 16, 17, 18, 25, 31, 32, 40, 41, 42, 51, 56, 58 and 60.

The DMUs that are common to these two sub-groups are numbers 17 and 31, from Rw and Iw systems respectively.

In Lam Sieo Yai basin (see appendix E), the systems with highest efficiencies are even fewer. Only DMUs number 17, 36 are technically efficient (>90%), and 17, 20, 58 are environmentally-efficient. DMU 17 is a Rw system.

The low efficiency overall, and the very poor overlapping between the two sub-groups are concerning issues. Results show that high technical efficiency does not go much along with high environmental efficiency. These results reiterate the ones shown by comparative performance analysis: technically-efficient systems are few, and different from the environmentally-efficient systems. In order to increase sustainability overall, trade-offs are required, and also, more specifically, technical efficiency has to augment seriously. It should lead to a decreased use of unnecessary inputs and resources, therefore resulting in higher environmental efficiency as well.

9.3.3 Potential reductions in production factors to achieve efficiency

DEA allows for identifying the potential reduction of input variables that would be required for an inefficient DMU to become fully efficient (i.e. joining the production frontier). Such potential reduction is the vector difference between the current positions of any DMU with the production curve drawn by the fully efficient DMUs.

Table 9.9 to 9.10 and (appendix E for details) show the potential reduction targets, in terms of environmental impacts and production factors (expressed in costs) for full environmental efficiency of Nam Mae Lao and Lam Sieo Yai basins, respectively.

In Nam Mae Lao basin, to achieve the optimal output, the median value of potential reduction of technical practices and environmental potential were mentioned in Table 9.9 and the details of each DMUs are shown in appendix e. The analysis suggests that farmers should reduce the production costs of 13-33% on fertilizers, 15-33% on pesticide application and 16-30% on machinery.

Table 9.10 shows the current average production costs per system, and potential reduction to achieve technical and environmental efficiencies in Lam Sieo Yai basins which can be used as the guideline for the farmers in this area.

Table 9.9 Current average production costs per system, and potential reduction to achieve technical and environmental efficiencies in Nam Mae Lao basin

Cropping systems	**Rw**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	12,188	4,256	-33.2
Pesticides	1,719	570	-33.2
Machinery	7,017	2,150	-30.7
Cropping systems	**Iw**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	12,188	1,652	-13.9
Pesticides	1,719	261	-15.2
Machinery	7,286	1,253	-16.7
Cropping systems	**Id**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	12,188	3,389	-27.8
Pesticides	1,719	485	-28.2
Machinery	7,432	2,028	-27.8

Table 9.10 Current average production costs per system, and potential reduction to achieve technical and environmental efficiencies in Lam Sieo Yai basin

Cropping systems	**Rw**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	12,188	2,499	-20.5
Pesticides	1,590	336	-20.5
Machinery	7,066	1,485	-21.4
Cropping systems	**Iw**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	13,375	3,233	-24.2
Pesticides	2,656	647	-24.3
Machinery	6,323	1,476	-23.1
Cropping systems	**Id**		
Costs	**Current production cost**	**Potential reduction**	**Difference from current costs %**
	(THB/ha)	**(THB/ha)**	
Fertilizers	13,375	8,739	-65.3
Pesticides	3,281	2,361	-71.9
Machinery	6,287	3,314	-63.8

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

The research covered many dimensions of Hom Mali rice cropping systems in two main production areas of Thailand. In spite of all efforts towards improved understanding, documentation, and quantification of the issues at stake, conclusions must be drawn with utmost caution. Indeed, it must be kept in mind that these results refer to one single year of cropping (2010), a relatively wet year. Techno-economic performances might be worse off in a normal or drier year, especially for Id systems in the water-scarce Northeast.

10.1 Summary of main results

10.1.1 Documenting Hom Mali rice cropping systems in the main production areas

First, the research provides a quantified and documented overview of Hom Mali rice cropping systems in its two main production areas, i.e. the North East and North regions. The two selected case study basin represent fairly well the respective situations of both regions.

The two basins are exposed to contrasted conditions. Nam Mae Lao basin benefits more rainfall, and is immune so far from the brown plant-hopper. In this Northern basin, irrigation systems are prevailing, with all-year round cropping and highest performances. Rainfed systems are fewer, and perform at lower levels, on all productivity indicators.

On the contrary, Lam Sieo Yai basin suffers dry season water scarcity, and damages by two prevailing pests: brown plant-hopper in dry season and golden snail in wet season in fields that are irrigated all-year round. Under such conditions, uncontrolled irrigation in wet season (Rw systems) prevails in techno-economic terms. Id systems are few and perform at lowest levels, on all productivity indicators.

The most important feature of the Hom Mali rice systems remains their relatively low yields, compared to national, regional and international references on other varieties. Also, this study confirms and documents the substitution of traditional transplanting by direct seedling techniques in Thailand, which further contributes to low yields. Dry seed sowing is the least labour-consuming method, the most detrimental to yields, and prevails in all systems in the North East, and rainfed systems in the North; wet seed sowing reflect higher intensification and prevails in irrigation systems in the North. Such changes in practices have had important consequences in terms of tillage, organic matter and water management requirements, leading to higher methane emissions, especially in irrigated systems.

It was also shown how water availability determines cropping intensity in the North East, where farmers are reluctant to grow rice under irrigation during the dry season. Only half of the plots that are irrigated in wet season are also cropped in dry season. In the North, most fields that are cropped during the wet season, under irrigation that supplements rainfall, are also cropped in the following dry season. Such succession is permitted by favorable climatic conditions and well-endowed irrigation systems in dry season.

Cropping calendars in both basins show striking features and differences, which were fully documented, for further research and use by practitioners.

Second, the research analyses the main issues in both basins, and the problematic systems. In Nam Mae Lao basin (North), the low performance of rainfed rice systems (Rw) is highlighted. In the basin, rainfed systems are clearly less intensive systems, which still use dry-seed seedling method. In Lam Sieo Yai basin (North East), Id systems are the low yielding ones. This is not related to seedling method since dry seed seedling now prevails in all systems, and results in lower yields overall. Rather, it was observed that conditions and practices are similar between Rw and Iw systems, while Id systems suffer from insufficient water supply and specific pests (brown plant-hopper). So in the two basins, the systems that concentrate most issues and yield lowest performances are different: rainfed systems in the North (Rw), dry-season irrigation systems (Id) in the Northeast. Interestingly, both these systems are the least implemented by farmers in both basins, respectively.

In both basins, the highest yielding system is Iw. Supplemental irrigation provided during the monsoon season, combined with high temperatures, ideally results in the highest performances of photosensitive Hom Mali rice.

In both basins, labor use and energy use are higher in Id systems because irrigation in dry seasons require more water pumping episodes on average to replenish ponding conditions in paddy fields; therefore, it requires more labor and energy. Combined with lower yields, these elements make Id systems least labor and energy productive.

Production costs per ha are quite homogenous across systems and basins. However, due to lower yields, net income is markedly lower in the Northeastern basin. Actually, farmers in Lam Sieo Yai basin pocket approximately half of what farmers earn in Nam Mae Lao basin, regardless of their cropping system. In both basins, Iw systems earn the highest net income.

10.1.2 Quantifying crop budgets and techno-economic performances

Farmers' practices proved very homogenous across cropping systems in both basins, showing particularly small variations in application of agrochemicals. The overall low diversity of agrochemicals used must also be underlined. Production costs per ha reflect such relative homogeneity of practices. Labour use shows much more diversity. In spite of the relative homogeneity of cropping practices, outcomes in both economic and environmental terms show significant diversity. Net income and global warming potential are particularly wide-ranging in the different systems. This variation mostly results from large differences in yields, overall and per sub-cropping system.

Overall, yields and resulting net incomes are more diverse in Rw and Id systems compared to Iw systems, due to a lack of control of the water supply and a lack of water, respectively. In terms of water use efficiency (crop water productivity), results from both basins point Id systems as the least water-efficient systems and Iw systems as the most water-efficient systems. Id systems in the Northeast are particularly water-inefficient compared to others, on account of low yields. Compared to international references, Hom Mali rice systems in Thailand are clearly inefficient in water use, due to low yields (with a diversity of non-water related limiting factors, including extensive cropping practices, and pest pressure), and also high ET conditions due to quasi-permanent flooding. Alternate wetting / drying conditions in paddy fields seems to lead to higher CWP, as highlighted by literature.

Agrochemical application doses are very homogenous, yet leading to contrasted yields. Apparent N recovery efficiency is low (20% in the North, 15% in the Northeast), lower than international best-practice, which highlight the detrimental combined effects of dry-seed direct seedling, permanent flooding, early single massive urea application.

Calculations of pesticide productivities in both basins confirm previous rankings: Rw systems in the North and Id systems in the Northeast show lesser productivity of all pesticides used.

10.1.3 Documenting and quantifying environmental impacts

As said, Hom Mali rice systems of Thailand are not highly-intensive cropping systems. Particularly, the limited use of pesticides results in limited environmental loads per area cropped, in terms of potentially impacting emissions. Yet, low yields make environmental loads per functional unit (kg rice) still significant. Overall, CH_4 and other GHG emissions prevail as environmental loads, due to cropping conditions, especially in irrigated systems Iw and Id.

All impacts per kg of paddy rice at farm gate are systematically higher in Id systems in Lam Sieo Yai basin, mostly due to lower yields, and water management practices.

Environmental ranking of systems is not so clear in the North. Impacts are also higher in Id systems of Nam Mae Lao basin, except for GWP (higher in Iw) and EP (higher in Rw). Also, land and energy requirements are higher in Rw in the North.

The higher GWP_{100} in Iw systems in the North and in Id systems in the Northeast are caused by higher CH_4 emissions, linked to shorter non-flooded per-season conditions, early incorporation of organic residues, and, in the North, Iw systems are continuously flooded. Overall, our results are consistent with other international studies, except for irrigation systems in Lam Sieo Yai basin, where GWP values double. It is important to highlight that, in spite of intermittant flooding conditions in Northeast, high methane emissions are still recorded there.

Overall, our results for Thai rice were either of similar magnitude yet greater (energy use, GWP, ODP, water use), or much greater (Acidification and Eutrophication potentials) compared to the results from other regions. This trend of LCA results per kg of rice being greater in our case study can globally be explained by rice yields being markedly lower in Thailand as well reflected by the sampled systems. Also, comparison of results from various sources clearly show that harmonised methods and assumptions would be desirable to complete LCA study comparisons across contrasted situations.

The contribution analyses in all systems show similar patterns, although total water use in Id systems results mostly from blue water use (irrigation water), while WU in Iw systems results mostly from the green water use (natural stocks and flows). Overall, direct field emissions are contributing a main part of input related impact categories at local and regional scales (AP, EP, FAETP) and on the global scale (GWP); they mostly depend on water management practices for methane emissions, and both agrochemical and water management for other emissions.

10.1.4 Studying sustainability in rice cropping systems in Thailand

Eco-efficiency analyses revealed that Iw systems yield higher return per impact than other systems in the North, while Rw systems prevail in the Northeast. Interestingly, Id systems are lagging behind in both basins.

Eco-efficiency ratios may be candidates as sustainability indicators; however, there are as many EE ratios as there are environmental impact indicators, which makes synoptic interpretation difficult. Also, using gross income or net income as a numerator makes a difference.

Technical efficiency analyses with DEA confirmed the results obtained with techno-economic performance analyses. In Nam Mae Lao basin, irrigated systems are the most technically efficient. In Lam Sieo Yai, Rw and Iw prevail and are close, while Id systems are lagging far behind.

Environmental efficiency analyses with DEA broadly confirm the results of LCA, yet they provide more information. They also reveal that Id systems are the least environmentally efficient in both basins, while Rw prevail in the Northeast, and are close with Iw in the North.

These results confirm that the hierarchy of systems in terms of sustainability is arguable. Overall, Iw systems and Rw systems alternatively prevail in techno-economic and environmental terms in both basins. One clear message is that Id systems are poor performers in both techno-economic and environmental dimensions, in the Northeast. They may be considered unsustainable.

TE and EE scores may be excellent surrogates to sustainability indicators, as they amalgamate the many techno-economic and environmental impact indicators in only two indicators per systems.

An analysis of deciles with high performers in techno-economic and environmental terms show that high net income is not compatible with low environmental impacts. Also, surprisingly, high income is not linked to low production costs, in both basins.

Similarly, analysis of deciles with highly efficient systems was carried out. It confirms that besides poor environmental efficiency overall, only very few systems achieve high TE and high EE.

Overall, trade-offs seem inescapable. Any attempt to improve the sustainability of Hom Mali rice systems in both basins would require compromise. Reduction in input and resource use, while sustaining yields seems to be the way forward, which requires increased efficiency of those inputs and resources. It seems that high economic return to production is not compatible with low production costs and low environmental impacts at the moment, under current practices and technology

Further DEA analyses reveal the potential for increased efficiency through input reduction. In particular, they show that efforts may be relatively balanced in the respective reduction of fertilizers, pesticides, and machinery use. They provide the magnitude of potential reductions required, and emphasis the target systems, i.e. Rw in the North and Id systems in the Northeast, where approximately 60% reduction of all inputs considered is required to achieve both TE and EE.

10.2 Scientific contributions of the research

10.2.1 What have been the truly novel contribution of research

The research performed and related in the present document is original and novel, from different perspectives:

First, this research is **the first of its kind done in Thailand**, addressing jointly techno-economic and environmental performances of rice cropping systems. Both the methodology mix used, and the many results gained may be of use to scholars, researchers, managers and policy-makers in Thailand.

Second, the research was **multi-disciplinary** in nature, combining classic (yet not so common in South East Asia) techno-economic analysis with ambitious Life Cycle Assessment of a large number of cropping systems, and many different tools and methodologies. Indeed, the research mobilized hydro-agricultural modeling to improve the inventory phase in LCA (for nutrient balances, field emissions and water use), WSI and water deprivation potential in small basins and the calculation of technical efficiency and environmental efficiency by using the combination of techno-economic analysis, LCA and DEA approaches. Overall, proper understanding of agronomic, technical, economic, and environmental engineering concepts and tools was required.

Third, the research relied mostly on **primary data**, which were collected in a large number of cropping units (120); such approach diverges from the typical techno-economic approaches based upon regional statistics.

Fourth, LCA application cases in agricultural production, although on the rise, remain rare, especially in non-OECD countries. Further, **the combination of LCA with DEA** is new and hardly applied in developing contexts. It proves extremely fruitful.

Fifth, efficiencies, and particularly **eco-efficiency** and **environmental efficiency** concepts, have been used to approach, quantify, and discuss the sustainability of the systems under study. Such approach is original. Eco-efficiency analysis based on value added per individual environmental impact is a common approach but to produce a single value of eco-efficiency through aggregating the environmental impacts is a challenging task. The contribution of this research is also that it produced a single value for eco-efficiency and environmental efficiency, respectively, as per any given system (using LCA indicators) for each system, as proxies to its sustainability. Such score also compensate for the lack of one single environmental impact score per system.

10.2.2 What water deprivation potential adds to the sustainability assessment?

Overall, our results concur with those obtained by Pfister et al. (2009) at broad regional level, and by Gheewala et al. (2014) at whole river basin level. However, we have shown that WSI calculated at the local (sub-basin) level with accurate data may be significantly different and more relevant than the ones calculated at broader levels, with low-definition data.

Calculated from WSI, the water deprivation potentials resulting from rice cultivation are also very different between basins. We advocate for the use of the method we used, at sub-basin level. It is simple, and requires data that is generally available from public authorities in charge of meteorology and hydrology monitoring in most countries.

Our contrasted case studies show how useful it may be to include WDP as an environmental impact to LCA work, to better discriminate production systems and highlight water deprivation risks. Mere water consumption values and even water footprinting figures cannot reveal such impact. The results from Northeast reiterate that further dry season irrigation development would potentially result in severe water deprivation.

10.3 Final recommendations, societal contributions

10.3.1 Developing further paddy rice irrigation in Thailand? contrasted results from North and Northeast regions

The results contribute insights and data to the debate on the need and features of irrigation development in Thailand, although with the necessary precautions due to limited spatial and temporal representativity of data. Results show that irrigated rice in the North (Nam Mae Lao) is performing better than rainfed rice, in all dimensions. The findings are very different in the North East (Lam Sieo Yai).

In northeast region, rainfed systems are reasonable alternatives and compete well against wet season irrigation. Proponents of irrigation development in North-east Thailand advocate that rain-fed systems only provide a cropping opportunity during the wet season and force farmers to resort to alternative livelihoods in the dry season. In any case, the Isaan region has a long tradition of rural seasonal immigration during the dry season and of off-farm and on-farm diversification of livelihood systems. Results on eco-efficiency concur with those on techno-economic performances (chapter 6) and environmental performances (chapter 7). It seems that irrigation during the dry season is not very profitable or environmentally friendly; in addition, this cropping system requires significant amounts of blue water, which must be tapped from existing limited resources at the expense of other users or the environment. In North-eastern regions, water supply is a problem for urban areas for instance since surface water is the only resource, with no major reservoir for storage; further irrigation development in dry season will only make the water scarcity issue more acute.

For a societal objective of higher rice production and limitation of immigration, irrigation during both seasons guarantees higher production overall, and keeps farmers busy all year round. From a farmer‘s viewpoint, dry-season irrigation requires more inputs, higher costs and labour, and ultimately shows lower efficiency. Because of such reasons, and the fact that irrigation water supply is not guaranteed, only half of irrigation farmers grow rice during the dry season in northeast region. Also, these farmers do not have alternative livelihoods, while wet season farmers are typically migrating during the dry season and/or own livestock.

Furthermore, if eco-efficiency and environmental integrity are factored into decisions, irrigation during the dry season is clearly not the best option. In spite of these poor performances, approximately half of the irrigation farmers grow rice during the dry season under irrigation. These farmers manage to access enough water.

Further, the striking shift from traditional transplanting to direct sowing of dry seeds illustrates the fact that rice farmers in Isaan are seeking labour efficiency and time-saving solutions, rather than high yields, in a context of labour scarcity, massive seasonal immigration, and diversified rural livelihood systems (ADB, 2012). Indeed, direct seedling results in lower yields than transplanting, yet with lower labour requirements. So, beside its higher environmental impacts and costs, rice systems' intensification through irrigation might not be the way chosen by the farmers.

10.3.2 How to improve sustainability in rice cropping in Thailand?

The original intention of this research was mostly to investigate the environmental impacts, performances and efficiency of Hom Mali rice production systems in Thailand. The idea was to contribute to better document in environmental terms the high quality, high value fragrant rice of Thailand as an export flagship product, possibly towards eco-labeling, or promotion of the rice Good Agricultural Practice scheme (rice-GAP).

During the course of the research, Thailand has actually lost its rank as first global rice exporter. It now ranks 3, 4 or 5, depending on sources. There are many political, institutional and financial reasons for such a drop. However, we claim that this research also identified technical and economic factors as key issues faced by rice production at the farm level.

Ever increasing labour scarcity (due to rural outmigration and farmers' aging) and labour costs are leading to increased mechanization costs and the resort to low-yielding practices such as direct sowing of dry seeds. Water scarcity and unreliable irrigation supply in the North East prevent the development of second-season rice. Overall, yields are very low compared to potential, and to regional and international records. Systems are broadly inefficient, both technically and environmentally. Also the research pointed out the diversity and dynamism of the systems at farm level. All of these issues have been clearly identified and documented; they should be addressed urgently.

Thailand has been spending massive public funds to support rice and irrigation over recent decades, especially through subsidies, financial schemes, and infrastructural development (Perret et al., 2013). More focused efforts should be targeted to the production systems themselves, at local level.

To that aim, the Royal Irrigation Department, the Rice Department of Thailand should be interested with the results and methodologies shown in this research. Policy makers could also benefit when revising the support strategies to rice production, especially in terms of production costs and environmental impact. The approach developed here may be useful to back-up the current schemes on rice GAP, and organic rice labeling, towards clarification of the real environmental and economic advantages of environmental-friendly rice cropping, and possibly clearer information to both farmers and final consumers.

The current approach of extension is rather top-down, with blanket, "one-fits-all" or blue-print recommendations, in a context of limited farmers' initiative and voice. Better understanding of current practices, their dynamic and diversity should be favored.

The disastrous yield gap, and broad technical and environmental inefficiencies should be truly recognized and addressed, with more active training, demonstration programs, on-farm experiments and promotion of farmer-to-farmer communication.

Yet, building upon current systems and farmers' experience may not suffice. More engaging policy measures and incentives to push trade-offs to happen may be needed. In particular, adaptations to predominant direct seedling techniques should be considered.

Also, dry-wet alternate water management sequences should be implemented to minimize GHG emissions. Urea single, massive application of small pellets (leading to low N use efficiency and massive volatilization) should be replaced by large pellets incorporation. Also, since most cropping systems still operate under increasing return to scale, there seem to remain certain limiting factors to production which do not allow the full expression of other inputs such as agrochemicals. Further research on irrigation scheduling, including alternate drying periods, and nitrogen fertilization, among others, may be needed to investigate.

10.4 What are the prospects for further research

Temporal variations always exist regarding input use and yield due to different climatic conditions. In this study only one year data has been used to assess techno-economic and environmental performances and efficiency analysis. To address this issue several year data is recommended future studies to make the results generalized. Our data collection documented only two cropping seasons in one given year. Techno-economic and environmental performances are very dependent upon climatic conditions (through yields, water balance, growing cycle length, scheduling of field operations, etc.). Further research should address other climatic scenarios (e.g., a typical dry year, an average year, a wet year), or even better, a sequence of several years. This research was of a synchronic nature (several systems assessed at one time); further research may consider a diachronic approach (a given system assessed over several cycles).

In this study, the environmental and techno-economic indicators have been calculated as means and medians for each class, with a minimum-maximum range (but not the variance within each class). Since most of the results consist of comparing and ranking systems, it would be interesting to have statistical analysis done on the data. Data mining, using for instance Principal Component Analysis, could reveal more relationships between variables, and possibly lead to clustering systems in different meaningful ways.

In rice cropping, direct field emissions form the bulk of environmental impacts. A thorough inventory cannot compensate for a lack of local references with regards to direct field emissions. Although ideal, field measurements (tier-3 data) are hardly feasible in conjunction with a research project such as the one performed here. However, the exclusive use of generic baseline emissions and factors (tier-1 data, such as the ones provided by IPCC) may lead to massive errors. This research tried to adapt IPCC standards and use some tier-2 information (regional data, compiled by Yan et al., 2003a; 2003b); it also attempted to more accurately model emissions to water. Yet, in order to improve inventory data overall in rice LCA in South East Asia, research efforts should focus on collecting further primary data from rice fields on GHG (CH_4, N_2O, NOx) emissions, in order to improve databases and models. Such measurements should consider the main cropping conditions, water and soil management patterns. Japan, South Korea and China have made significant progress in those aspects, which should now also be considered in South East Asia (Thailand, Vietnam, Myanmar) where most export rice originates from.

To compensate for the lack of tier-3 and tier-2 data, uncertainty analysis should be performed. Ranges of plausible variations in emission factors could be included in Monte-Carlo analyses, or single-variable sensitivity analyses, in order to check the sensitivity of the results (environmental impacts) to such variations.

The type of research performed here is demanding. It is multidisciplinary by nature, requires a huge primary data basis and involves complex modelling. However, such methodological combination shows great potential for multi-criteria assessment of cropping systems and allows for detailed eco-efficiency analyses. Several sensitive aspects and key limitations shall be underlined and possibly addressed in future research undertaken with a similar approach.

Results on eco-efficiency are presented per impact category; several eco-efficiency indicators are calculated and shown for each system. Such profusion is difficult to communicate for decision- and policy-making purposes, especially when ambiguous results or interpretation occur or when eco-efficiency indicators on a given system show contradicting results. Trade-offs and possibly weighting and normalization of the impacts are needed. We have used DEA to generate a single environmental efficiency indicator per system. It solves the multiple eco-efficiency indicators issue, and compensate for the lack of one single-score environmental impacts (as provided by EcoIndicator 99 or Recipe methods). Yet, environmental impacts may be weighted differently, which is easily done with DEA. More research is needed, in collaboration with decision-makers, on this weighting issue.

It would be the interesting to develop a benchmarking approach in future research, coupled with the testing of a monitoring and advisory system towards farmers. This present research identifies avenues (especially with the combination of DEA and LCA) for such ventures, to link up efficiency analyses, the comparison of existing systems’ performances, and their ultimate improvement towards increased sustainability.

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APPENDIX A

QUESTIONNAIRE AT FARM LEVEL

Mrs. Kwansirinapa Thanawong **Questionnaire No._____**

A combined analysis of techno-economic performances, water resource use and potential environmental impact in rice cropping system:
Case studies in selected regions of Thailand

Survey Questionnaire at Farm level

1. General information of farm owner

Name and family name of farmer..

Address..

....

Telephone.. E-mail address...

Name and family of farm manager (if any)...

Address..

....

Telephone.. E-mail address...

2. Farm location

Land area...(Rai)

Address..

....

3. **Farm map**, showing the routes and distinguishable place nearby for convenience to reach the farm. Indicate the adjacent plots and also farm water sources**.**

4. The history of land used within the past three years: Indicate the type of crop/variety grown

1st Year..................................2nd Year....................................3rd Year...................................

5. Cultivation practice ☐ transplanting ☐ wet seeded ☐ dry seeded

6. Rice seed source

Varietal name	Area (rai)	Seed source	Distance from source (km)	Type of vehicle	Oil/fuel consumption (liters)	Seed used (kg)	Seed rate (kg/rai)	Price (Baht)

Please answer the following question based on the growing of *Kao Dok Mali 105* (the variety of jasmine rice)

7. Jasmine rice production

Area cultivated......................................rai

Area harvesting.....................................rai

Threshed jasmine rice production or yield...kg/rai

Price of threshed jasmine rice at the farm (price/kg)...Baht

Price of threshed jasmine rice (price/kg)...Baht

8. Field operation

8.1 Human Labor

No.	Type of operation	Area (rai)	Family labors			Hired labors			
			Family labors	Total (days)	Working Time	No. of labors	Total (days)	Working Time	Wage/day
1	Land operation								
2	Transplanting rice								
	2.1 land preparation								
	2.2 sowing								
	2.3 transplanting								
3	Sowing								

Human Labor (Cont'd)

No.	Type of operation	Area (rai)	Family labors			Hired labors			
			Family labors	Total (days)	Working Time	No. of labors	Total (days)	Working Time	Wage/day
4	Fertilizer application								
	4.1 chemical								
	4.2 organic								
5	Pest and weed management								
	5.1 insecticide								
	5.2 pesticides								
	5.3 herbicides								
	5.4 fungicides								
	5.5 raticides								
	5.7 Other..................								
	5.8 Other..................								
	5.9 Other..................								
	5.10 Other................								
6	Water management								
7	Harvesting								
8	Threshing								

8.2 Tractor

Source of Tractor: ☐ Owner ☐ Rental

If using the rental Tractor: Cost of the rental..................................(Baht/rai) or (Baht/day)

No.	Type of operation	Name	Model	Working time (hrs/day)	Total time (days)	Oil/fuel consumption for working (liters)	Oil/fuel consumption for rallying (l/hrs)	House power (hp)
1.	Land operation							
	1.1 tillage							
	1.2 puddling							
	1.3 plough							
	1.4 other................							
	1.5 other................							
2	Transplanting rice Land operation							
	2.1 tillage							
	2.2 puddling							
	2.3 plough							
	2.4 other................							
	2.5 other................							

8.3 Machinery

No.	Type of operation	Name	Model	Working time (hrs/day)	Total time (days)	rental machinery: cost (Baht/day)	Oil/fuel consumption (liters)	House power (hp)
1	Land operation							
2	Transplanting rice							
	2.1 land preparation							
	2.2 sowing							
	2.3 transplanting							
3	Sowing							
4	Fertilizer application							
	4.1 chemical							
	4.2 organic							
5	Pest and weed management							
	5.1 insecticide							
	5.2 pesticides							
	5.3 herbicides							
	5.4 fungicides							
	5.5 raticides							
	5.7 Other.................							
	5.8 Other................							
	5.9 Other.................							
	5.10 Other...............							
6	Water management							
7	Harvesting							
8	Threshing							

8.4 Water pump

Pump type..Diameter of pipe...

Fuel consumption..Horse Power (hp)...

Pump discharge...Head of water..

Pump operating time.....................................

8.5 How do you think about adequacy of water?

☐ always enough and timely
☐ o.k.
☐ not always good but cannot complain
☐ not so good, not enough or not in time
☐ hardly ever o.k. (not enough and not in time)

8.6 Animal Draft and water use

No.	Type of operation	Area (rai)	Animal Draft			Water use	
			Type of animal	No. of Animals	Working time	mm/rai	sources
1	Land operation						
2	Transplanting rice						
	2.1 land preparation						
	2.2 sowing						
	2.3 transplanting						
3	Sowing						
4	Fertilizer application						
	4.1 chemical						
	4.2 organic						
5	Pest and weed management						
	5.1 insecticide						
	5.2 pesticides						
	5.3 herbicides						
	5.4 fungicides						
	5.5 raticides						
	5.7 Other..................						
	5.8 Other..................						
	5.9 Other..................						
	5.10 Other.................						
6	Water management						
7	Harvesting						
8	Threshing						

9. Fertilizer application

Name of fertilizer	Formula of N-P-K	Application rate (kg/rai)	Active ingredients (%)	Total use (kg/ha)	Price (price/unit)

10. Do you understand about the effect of using fertilizer to soil quality?

☐ very bad ☐bad ☐average ☐good ☐excellent

11. Pest, weed and other chemical management

Name	Name of pesticide/ Weed control/chemical	Application rate (kg/rai)	Active ingredients (%)	Total use (kg/rai)	Price (price/unit)
1. Diseases					
1.1					
1.2					
1.3					
1.4					
1.5					
1.6					
1.7					
1.8					
1.9					
1.10					
2. Insects					
2.1					
2.2					
2.3					
2.4					
2.5					
2.6					
2.7					
2.8					
2.9					
2.10					

Pest, weed and other chemical management (Cont'd)

Name	Name of pesticide/ Weed control/chemical	Application rate (kg/rai)	Active ingredients (%)	Total use (kg/rai)	Price (price/unit)
3. Weeds					
3.1					
3.2					
3.3					
3.4					
3.5					
3.6					
3.7					
3.8					
3.9					
3.10					
4. Animals pests					
4.1					
4.2					
4.3					
4.4					
4.5					
4.6					
4.7					
4.8					
4.9					
4.10					

12. Sprayer or other implements use during the chemical application

Name	Specific model name	Power (hp)	Oil/Fuel consumption	Cost (Baht/day)

13. Did you use tractor, machinery, sprayer or other implements for other crops? If yes, please describe that how many percentage of using these implements for jasmine rice and other crops

Name of implements	Crops Name	Percentage (%)

13. (Cont'd)

Name of implements	Crops Name	Percentage (%)

14. Harvesting and threshing practices

Case 1: Harvest and thresh by labor

Performance	Notice
1. Blooming 80%	☐ Blooming consistently throughout rice field. ☐ Blooming inconsistently throughout rice field.
2. Water drainage	☐ Water draining seven days before harvest. ☐ Water draining longer than 10 days before harvest. ☐ No water draining.
3. Panicle performance	☐ Turn yellow completely. ☐ Three quarters of panicle turn yellow. ☐ Whole panicle remains green. ☐ Panicle over dried.
4. Harvest by ☐ labor ☐ machine	Field condition ☐ Dried ☐Wet
5. Drying ☐ Drying on a court for........days	☐ On a cement court ☐ On ground lay under with...................................... ☐ Clean the court by...
☐ Drying in rice field for......days	Sunlight ☐ Strong ☐ Medium ☐ Cloudy ☐ Rain ☐ others.................................
☐ Drying rice panicle in bundle for........days	Sunlight ☐ Strong ☐ Medium ☐ Cloudy ☐ Rain ☐ others.................................
☐ Drying rice panicle field laying in line on top of straw for......... days	Sunlight ☐ Strong ☐ Medium ☐ Cloudy ☐ Rain ☐ others.................................
6. Rice pile up in stack.	Amount.............................stacks

Case 1: Harvest and thresh by labor (Cont'd)

Performance	Notice
7. Threshing ☐ Labor ☐ Threshing machine ☐ Animal	☐ Same variety of rice was harvested from last crop. ☐ Different variety of rice was harvested from last crop. Explain cleaning practice. ☐ Others..
8. Total Produce	☐ Sale paddy in form of wet grain...................................ton. ☐ Safe for seeding / self consumption.............................ton.

Case 2: Harvest and thresh rice by machine

Performance	Notice
1. Blooming 80%	☐ Blooming consistently throughout rice field. ☐ Blooming inconsistently throughout rice field. ☐ ....
2. Water drainage	☐ Water draining seven days before harvest. ☐ Water draining longer than 10 days before harvest. ☐ No water draining.
3. Panicle performance	☐ Turn yellow completely. ☐ Three quarters of panicle turn yellow. ☐ Whole panicle remains green. ☐ Panicle over dried.
4. Harvesting date	Field condition ☐ Dried ☐Wet
5. Harvesting machine	☐ Last harvest was the same variety. ☐ Last harvest was different variety Indicate name.. (If known) Indicate cleaning method to eliminate remaining grain.. ☐ Others..
6. Total Produce	☐ Sale paddy in form of wet grain...................................ton. ☐ Safe for seeding / self consumption.............................ton.

15. Drying practice (If produce is sold in form of wet paddy, omit this clause).

Dry date: Starting date... Finish date..

Performance	Criteria
1. Performance of drying court. ☐ Ground courty. ☐ Cement courty. ☐ Asphalt court.	☐ Thickness of paddy layer is less than 5 cm. ☐ Thickness of paddy layer is 5-10 cm. ☐ Thickness of paddy layer is greater 10cm.
2. The last drying on this courty was on ....(date).	☐ Other produce... ☐ Rice (variety name)..................................... ☐ Other activity..
3. Material lay under produce during drying.	☐ None ☐ Canvas/plastic ☐ Net ☐ Others..
4. Cleaning drying court.	☐ None ☐ Sweeping ☐ Others (indicate)..
5. The sun shines condition (in general).	☐ Strong sunlight ☐ Medium sunlight ☐ Cloudy ☐ Rain ☐ Others..
6. Turn over paddy during drying.	Frequency of turning over paddy..................... time/day
7. Drying period.	Number drying day.......................days
8. Material used for covering paddy during drying period.	☐ none ☐ cover paddy with..
9. Dryer.	☐ Last drying was.................(indicate variety) ☐ Cleaning to eliminate grain remaining in the machine... Drying time: Starting at.........o'clock am or pm until.................o'clock am or pm. Drying duration..................hours.

16. Transportation

16.1 Transportation from farm to storehouse

Before transportation, what's kind of parcel/container that use for packing the threshed jasmine rice?
....

Capacity of parcel/container...kg

Distance..km

Type of vehicle...

Capacity of vehicle...ton

Oil/fuel consumption..liters/round

16.2 Transportation from storehouse to mill

Mill name..

Mill location..

Distance..km

Type of vehicle...

Capacity of vehicle..ton

Oil/fuel consumption..liters/round

17. Irrigation information

17.1 Distribution water to Individual Field

☐ By pumping ☐ By gravity ☐ Other (specify)..................................

17.2 Type of irrigation Practice

☐ Surface (furrow, border, basin) ☐ Sub surface (drip)

☐ Over head (sprinkler irrigation) ☐ Other (specify)..

17.3 water supply

Crop	Dry season			Wet season		
	1st crop	2nd crop	3rd crop	1st crop	2nd crop	3rd crop
Crop name						
Area cultivated (rai)						
Irrigated area (rai)						
How many times do farmer get irrigation water during the crop cycle (dry season)?						
How much irrigation water delivery to the field (m^3/s or m^3) per one time?						
How many hours irrigation water delivery to the field per one time?						

18. Crop information

18.1 Crop calendar

Variety of rice	Dry season						Wet season					
	Month											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.

18.2 Crop production

Crop	Dry season			Wet season		
	1st crop	2nd crop	3rd crop	1st crop	2nd crop	3rd crop
Area cultivated (rai)						
Area harvested (rai)						
Crop production or yield (kg/rai)						
Price of crop at farm (price/kg)						
Market price (price/kg)						

19. Income

Selling and Farm Revenue

Description	Dry season			Wet season		
	1st crop	2nd crop	3rd crop	1st crop	2nd crop	3rd crop
Product sold (price)						
Self consumption (kg)						
Selling value (price)						

APPENDIX B

DETAIL RESULTS ON TECHNO-ECONOMIC PERFORMANCES OF RICE CROPPING SYSTEMS

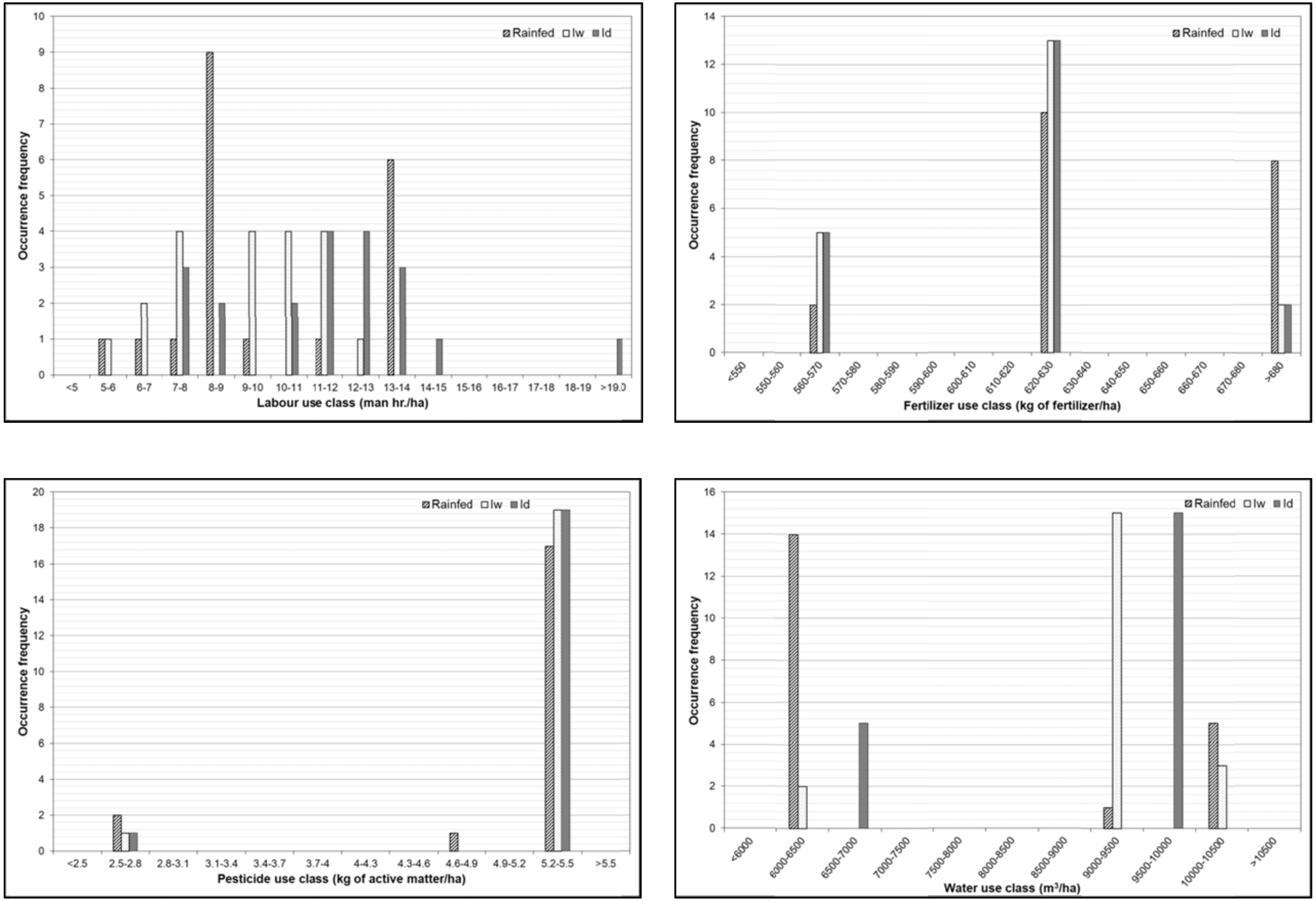

Figure B-1 The diversity of techno-economic performances per area cultivated in Nam Mae Lao basin – year 2010

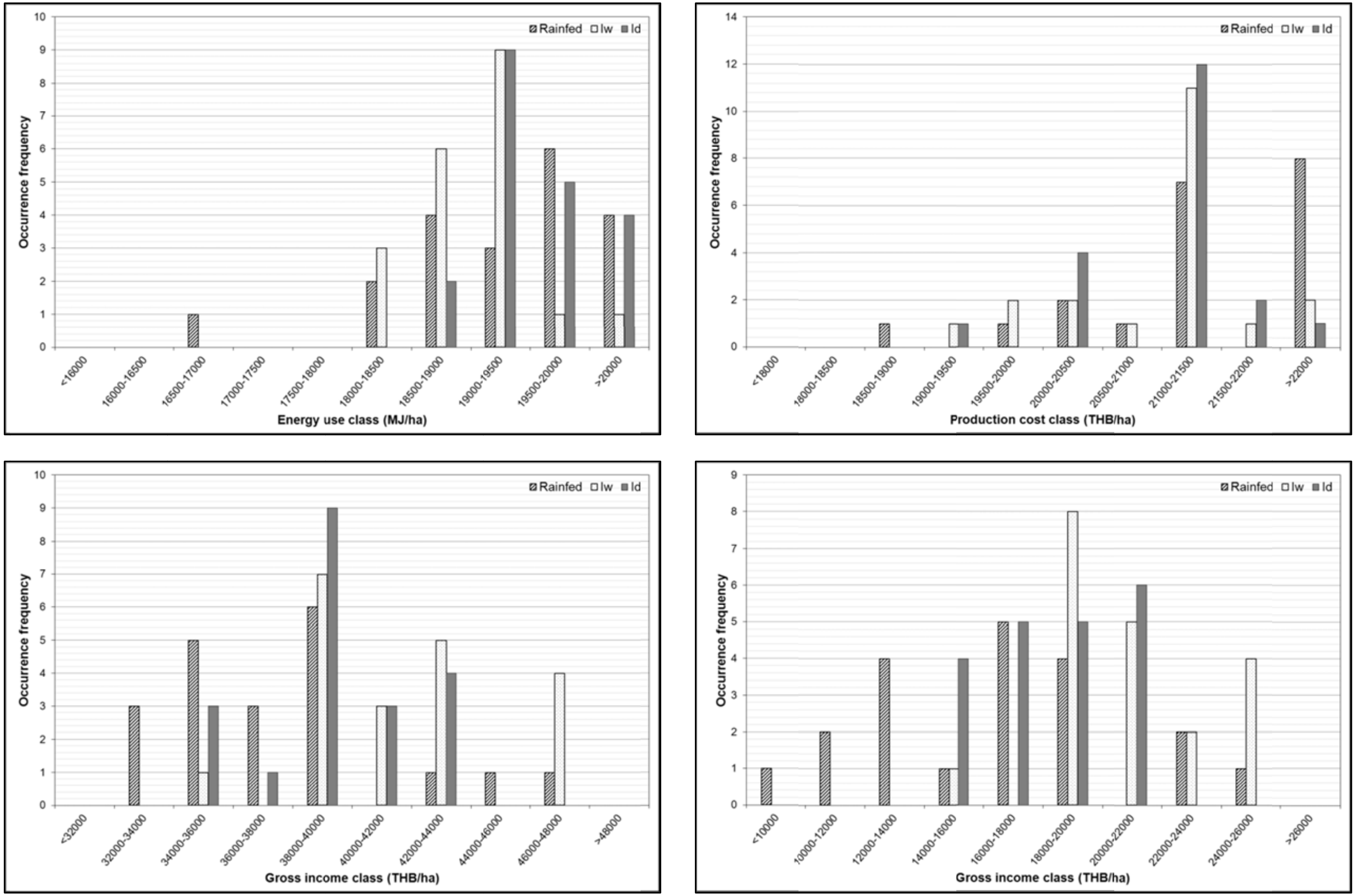

Figure B-1 The diversity of techno-economic performances per area cultivated in Nam Mae Lao basin – year 2010 (Cont'd)

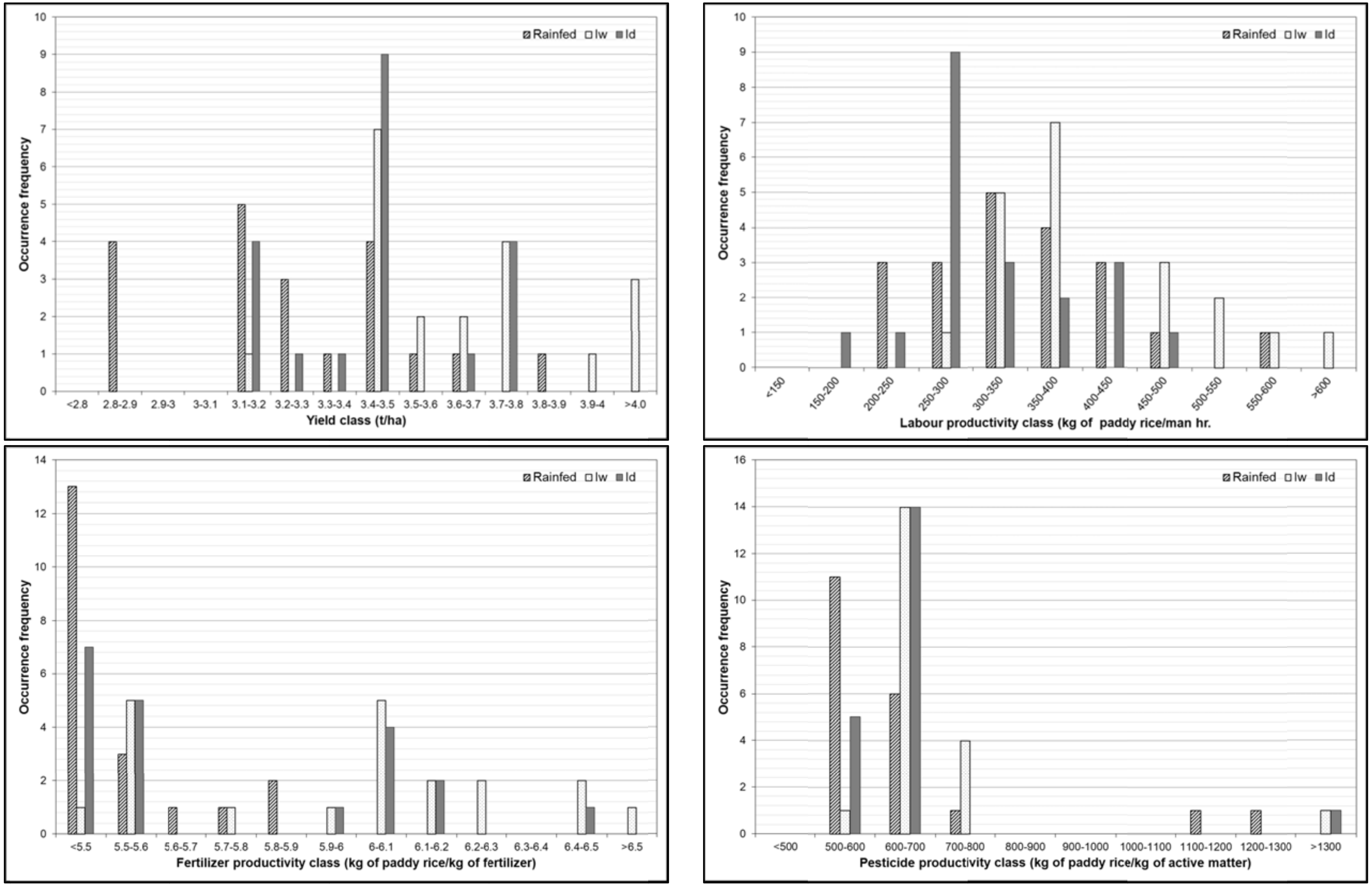

Figure B-2 The diversity of production factors' productivities and techno-economic performances in Nam Mae Lao basin

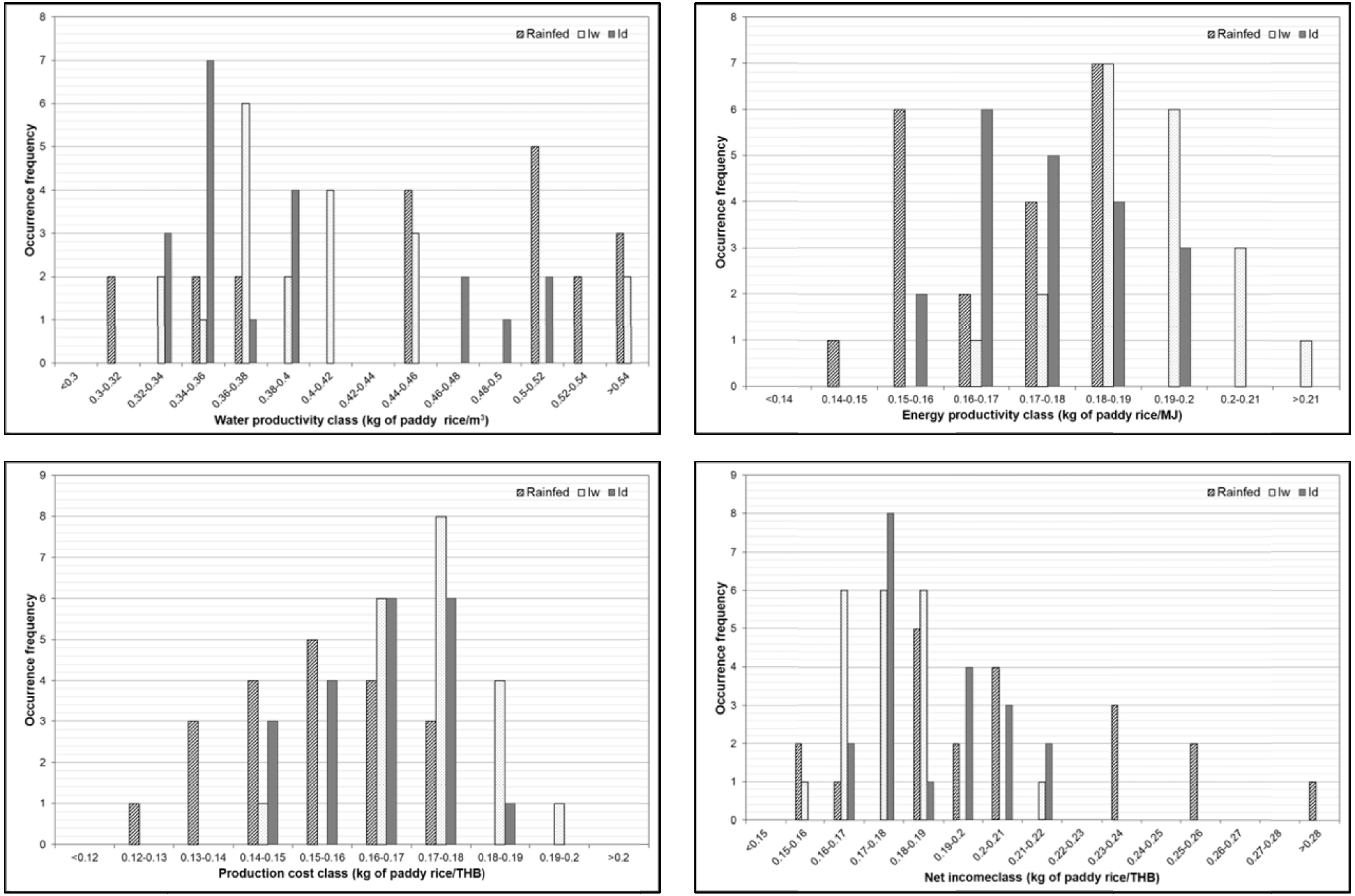

Figure B-2 The diversity of production factors' productivities and techno-economic performances in Nam Mae Lao basin (Cont'd)

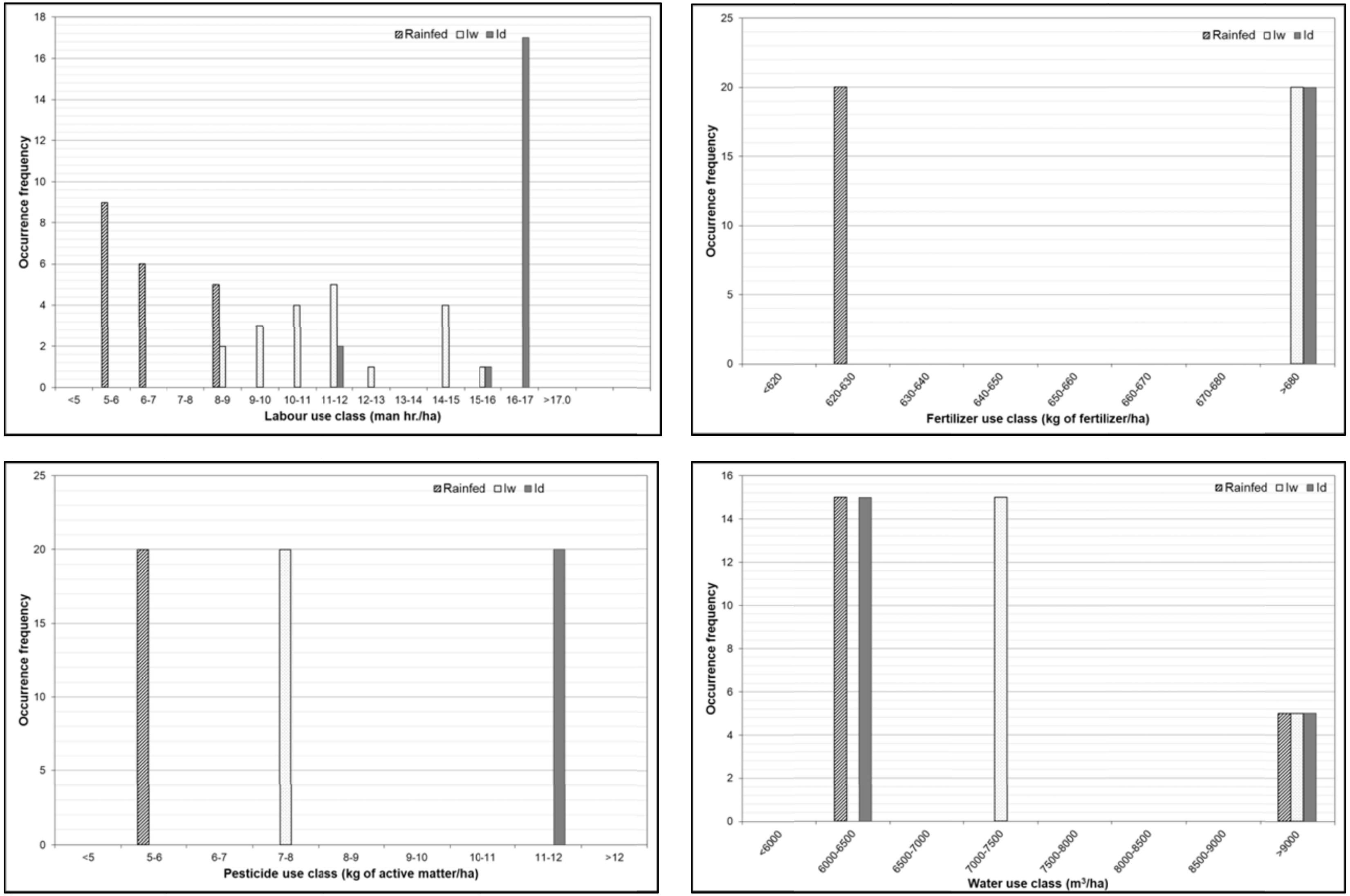

Figure B-3 The diversity of techno-economic performances per area cultivated in Lam Sieo Yai basin – year 2010

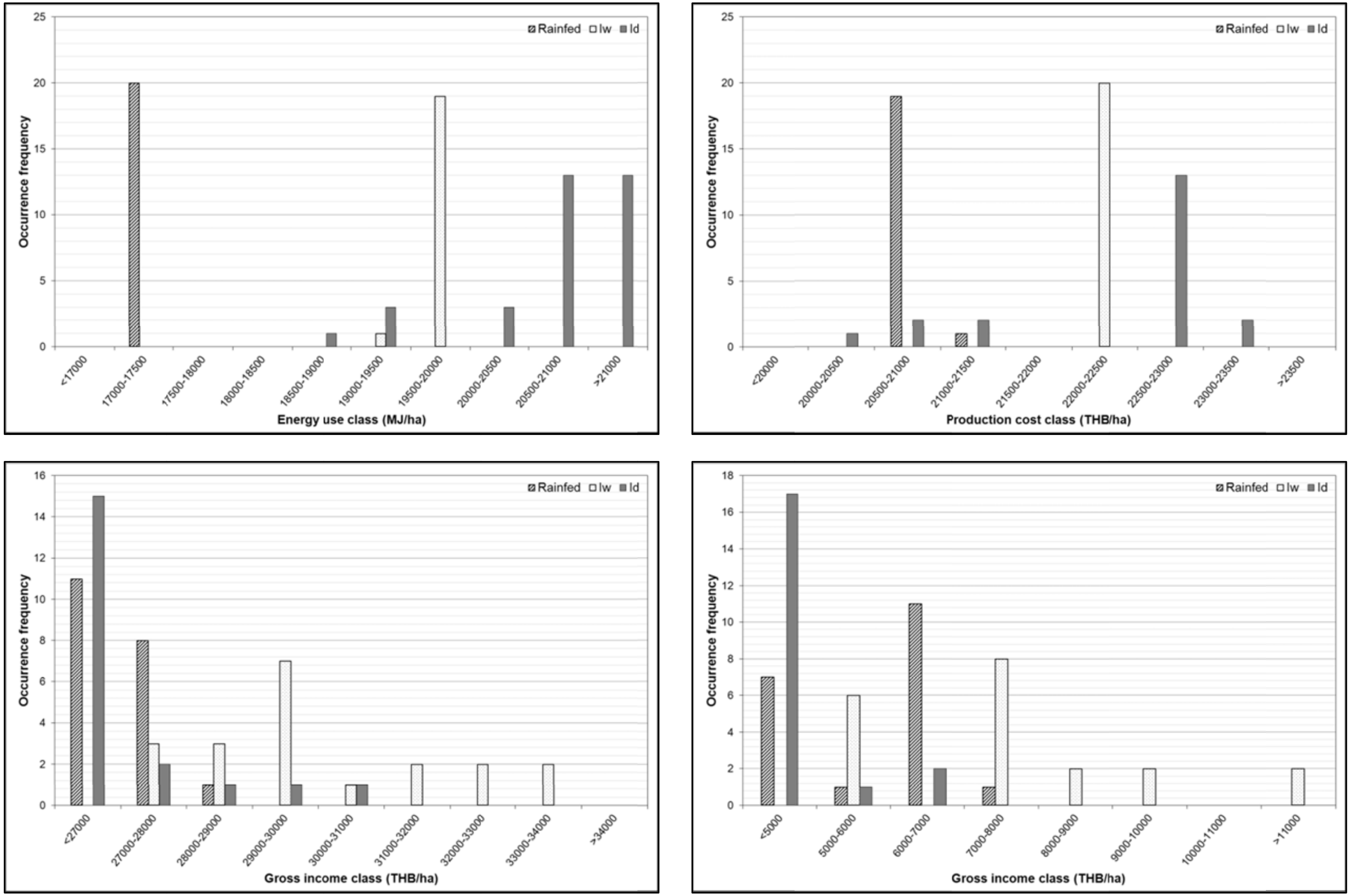

Figure B-3 The diversity of techno-economic performances per area cultivated in Lam Sieo Yai basin – year 2010 (Cont'd)

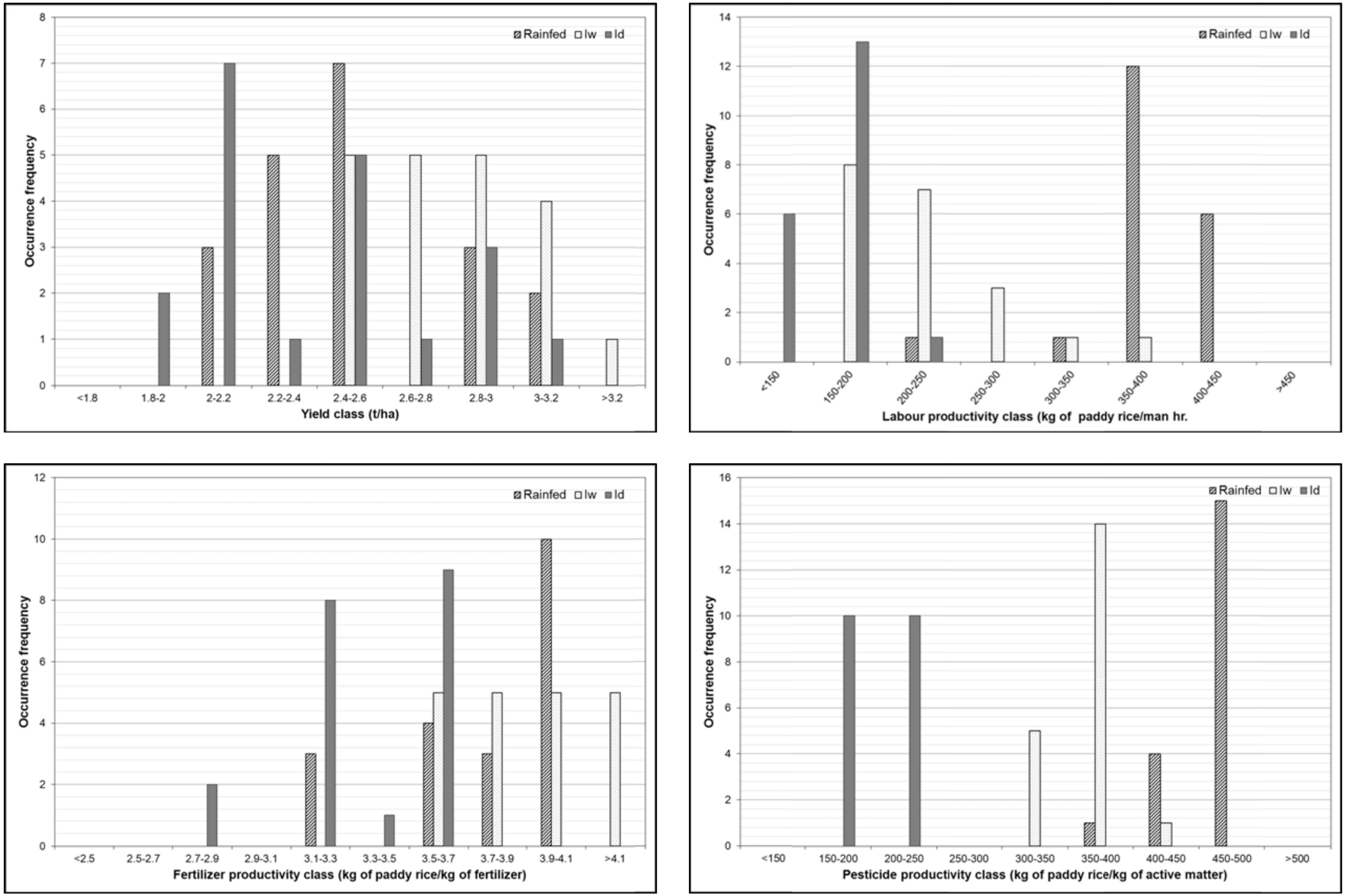

Figure B-4 The diversity of production factors' productivities and techno-economic performances in Lam Sieo Yai basin

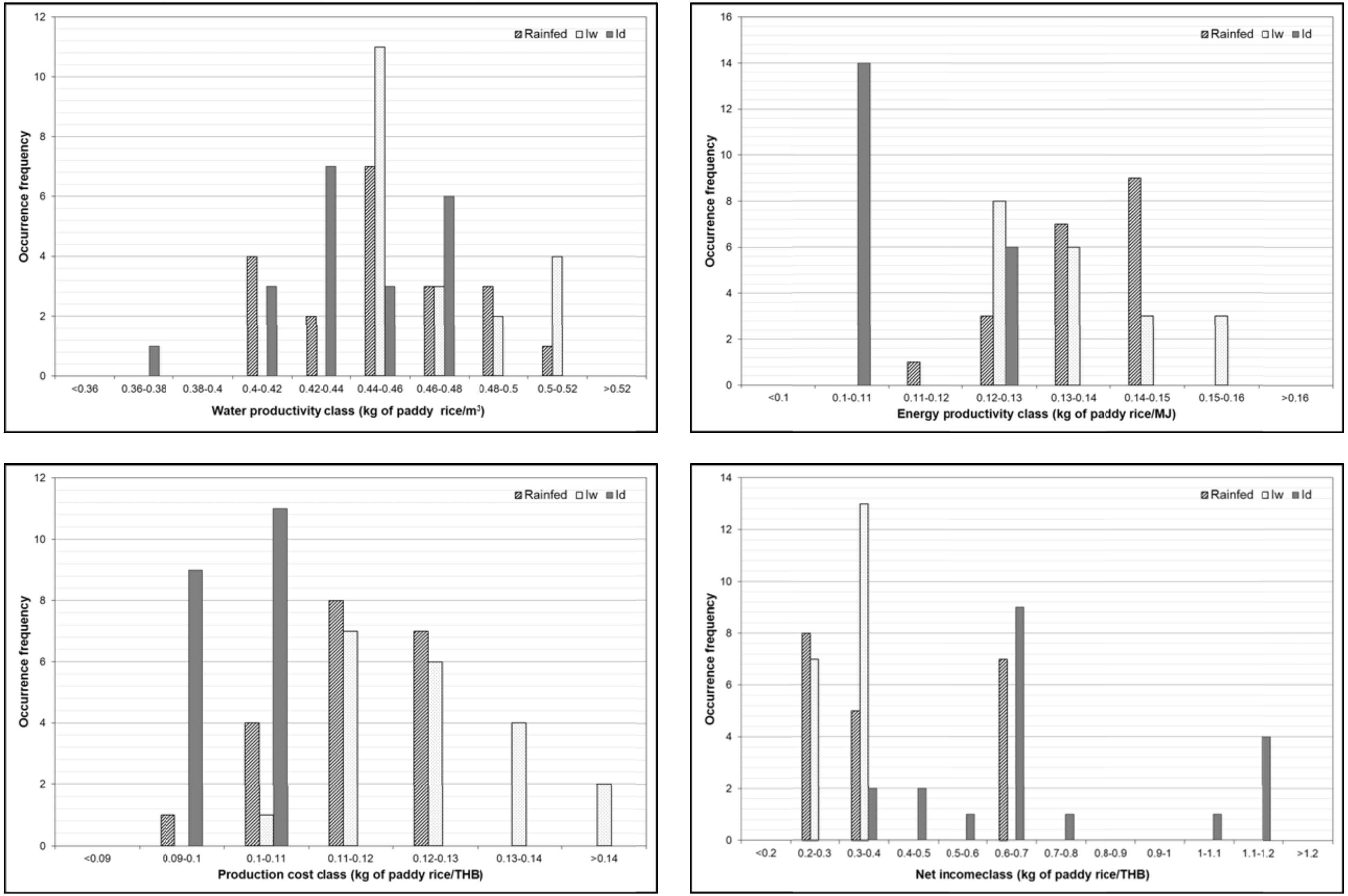

Figure B-4 The diversity of production factors' productivities and techno-economic performances in Lam Sieo Yai basin (Cont'd)

APPENDIX C

LCI DATA AND LCIA RESULTS

LCI data

Field operations

System			Rainfed						
Field process			Tillage operations	Tillage operations	Sowing	Water management	Fertilizing	Application of plant protection products	Harvesting
Database entry			Tillage, ploughing	Tillage, rolling	Sowing	Irrigating	Fertilizing	Application of plant protection products, by field sprayer	Combine harvesting
Reference unit			ha	ha	ha	m^3	ha	ha	ha
DMU	**1**	**Dry seeded**	0.0003556	0.0003556	0.0003556	0.0001404	0.0003556	0.0003556	0.0003556
	2		0.0003077	0.0003077	0.0003077	0.0001215	0.0003077	0.0003077	0.0003077
	3		0.0003200	0.0003200	0.0003200	0.0001579	0.0003200	0.0003200	0.0003200
	4		0.0002909	0.0002909	0.0002909	0.0000930	0.0002909	0.0002909	0.0002909
	5		0.0003556	0.0003556	0.0003556	0.0000702	0.0003556	0.0003556	0.0003556
	6		0.0002909	0.0002909	0.0002909	0.0000930	0.0002909	0.0002909	0.0002909
	7		0.0003200	0.0003200	0.0003200	0.0001474	0.0003200	0.0003200	0.0003200
	8		0.0003200	0.0003200	0.0003200	0.0001263	0.0003200	0.0003200	0.0003200
	9		0.0003556	0.0003556	0.0003556	0.0001633	0.0003556	0.0003556	0.0003556
	10		0.0003200	0.0003200	0.0003200	0.0000789	0.0003200	0.0003200	0.0003200
	11		0.0003019	0.0003019	0.0003019	0.0001192	0.0003019	0.0003019	0.0003019
	12		0.0002909	0.0002909	0.0002909	0.0001340	0.0002909	0.0002909	0.0002909
	13		0.0003200	0.0003200	0.0003200	0.0001474	0.0003200	0.0003200	0.0003200
	14		0.0003556	0.0003556	0.0003556	0.0001633	0.0003556	0.0003556	0.0003556
	15	**Wet Seeded**	0.00029	0.00029	0.00029	0.86669	0.00029	0.00029	0.00029
	16	**Transplanting**	0.0002716	0.0002716	0.0002716	0.8151783	0.0002716	0.0002716	0.0002716
	17		0.0002807	0.0002807	0.0002807	0.8423684	0.0002807	0.0002807	0.0002807
	18		0.0002591	0.0002591	0.0002591	0.7775709	0.0002591	0.0002591	0.0002591
	19		0.0003062	0.0003062	0.0003062	0.9189474	0.0003062	0.0003062	0.0003062
	20		0.0003062	0.0003062	0.0003062	0.9189474	0.0003062	0.0003062	0.0003062

Field operations (Cont'd)

System			Wet-Season Irrigated rice						
Field process			Tillage operations	Tillage operations	Sowing	Water management	Fertilizing	Application of plant protection products	Harvesting
Database entry			Tillage, ploughing	Tillage, rolling	Sowing	Irrigating	Fertilizing	Application of plant protection products, by field sprayer	Combine harvesting
Reference unit			ha	ha	ha	m^3	ha	ha	ha
DMU	**1**	**Dry seeded**	0.0002909	0.0002909	0.0002909	0.0000522	0.0002909	0.0002909	0.0002909
	2		0.0002909	0.0002909	0.0002909	0.0000498	0.0002909	0.0002909	0.0002909
	3	**Wet Seeded**	0.0002462	0.0002462	0.0002462	0.7385777	0.0002462	0.0002462	0.0002462
	4		0.0002667	0.0002667	0.0002667	0.8002632	0.0002667	0.0002667	0.0002667
	5		0.0003200	0.0003200	0.0003200	0.9602947	0.0003200	0.0003200	0.0003200
	6		0.0002667	0.0002667	0.0002667	0.8001158	0.0002667	0.0002667	0.0002667
	7		0.0002807	0.0002807	0.0002807	0.8422161	0.0002807	0.0002807	0.0002807
	8		0.0002909	0.0002909	0.0002909	0.8728469	0.0002909	0.0002909	0.0002909
	9		0.0002909	0.0002909	0.0002909	0.8729091	0.0002909	0.0002909	0.0002909
	10		0.0002909	0.0002909	0.0002909	0.8729091	0.0002909	0.0002909	0.0002909
	11		0.0002759	0.0002759	0.0002759	0.8278403	0.0002759	0.0002759	0.0002759
	12		0.0002667	0.0002667	0.0002667	0.8001053	0.0002667	0.0002667	0.0002667
	13		0.0002909	0.0002909	0.0002909	0.8729091	0.0002909	0.0002909	0.0002909
	14		0.0002909	0.0002909	0.0002909	0.8729091	0.0002909	0.0002909	0.0002909
	15		0.0002649	0.0002649	0.0002649	0.7949460	0.0002649	0.0002649	0.0002649
	16		0.0002388	0.0002388	0.0002388	0.7165139	0.0002388	0.0002388	0.0002388
	17		0.0002462	0.0002462	0.0002462	0.7387045	0.0002462	0.0002462	0.0002462
	18	**Transplanting**	0.0002559	0.0002559	0.0002559	0.7677976	0.0002559	0.0002559	0.0002559
	19		0.0002854	0.0002854	0.0002854	0.8563734	0.0002854	0.0002854	0.0002854
	20		0.0002759	0.0002759	0.0002759	0.8278276	0.0002759	0.0002759	0.0002759

Field operations (Cont’d)

System				Dry-Season Irrigated rice						
Field process				Tillage operations	Tillage operations	Sowing	Water management	Fertilizing	Application of plant protection products	Harvesting
Database entry				Tillage, ploughing	Tillage, rolling	Sowing	Irrigating	Fertilizing	Application of plant protection products, by field sprayer	Combine harvesting
Reference unit				ha	ha	ha	m^3	ha	ha	ha
DMU	**1**	**Dry seeded**	0.0003200	0.0003200	0.0003200	1.2704574	0.0003200	0.0003200	0.0003200
	2		0.0003077	0.0003077	0.0003077	1.2215911	0.0003077	0.0003077	0.0003077
	3		0.0002909	0.0002909	0.0002909	1.1549632	0.0002909	0.0002909	0.0002909
	4		0.0002909	0.0002909	0.0002909	1.1551005	0.0002909	0.0002909	0.0002909
	5		0.0003200	0.0003200	0.0003200	1.2706105	0.0003200	0.0003200	0.0003200
	6	**Wet Seeded**	0.0002667	0.0002667	0.0002667	1.8587825	0.0002667	0.0002667	0.0002667
	7		0.0002909	0.0002909	0.0002909	2.0277512	0.0002909	0.0002909	0.0002909
	8		0.0002909	0.0002909	0.0002909	2.0277560	0.0002909	0.0002909	0.0002909
	9		0.0003200	0.0003200	0.0003200	2.2306000	0.0003200	0.0003200	0.0003200
	10		0.0002909	0.0002909	0.0002909	2.0278182	0.0002909	0.0002909	0.0002909
	11		0.0002759	0.0002759	0.0002759	1.9230127	0.0002759	0.0002759	0.0002759
	12		0.0002667	0.0002667	0.0002667	1.8587719	0.0002667	0.0002667	0.0002667
	13		0.0002909	0.0002909	0.0002909	2.0278182	0.0002909	0.0002909	0.0002909
	14		0.0003200	0.0003200	0.0003200	2.2306000	0.0003200	0.0003200	0.0003200
	15		0.0002667	0.0002667	0.0002667	1.8589123	0.0002667	0.0002667	0.0002667
	16		0.0002909	0.0002909	0.0002909	2.0277533	0.0002909	0.0002909	0.0002909
	17		0.0002667	0.0002667	0.0002667	1.8589298	0.0002667	0.0002667	0.0002667
	18	**Transplanting**	0.0002918	0.0002918	0.0002918	1.9773799	0.0002918	0.0002918	0.0002918
	19		0.0003009	0.0003009	0.0003009	2.0449721	0.0003009	0.0003009	0.0003009
	20		0.0002904	0.0002904	0.0002904	1.9732187	0.0002904	0.0002904	0.0002904

Application of fertilizers

System			Rainfed									
Commercial Name			Hua-Wua-Kun-Tai	46-0-0	Hua-Wua-Kun-Tai	15-15-15			Commercial Name	16-20-0		
Active Ingredient			Urea, as 46%N	N	15%N – 15%P_2O_5 – 15%K_2O	N	P	K	16%N – 20%P_2O_5 – 0%K_2O	N	P	K
DMU	**1**	**Dry seeded**	0.1111111	0.0511111	0.0555556	0.0083333	0.0083333	0.0083333	0.0555556	0.0088889	0.0111111	0.0000000
	2		0.0961538	0.0442308	0.0480769	0.0072115	0.0072115	0.0072115	0.0480769	0.0076923	0.0096154	0.0000000
	3		0.1000000	0.0460000	0.0600000	0.0090000	0.0090000	0.0090000	0.0600000	0.0096000	0.0120000	0.0000000
	4		0.0909091	0.0418182	0.0545455	0.0081818	0.0081818	0.0081818	0.0545455	0.0087273	0.0109091	0.0000000
	5		0.1111111	0.0511111	0.0555556	0.0083333	0.0083333	0.0083333	0.0555556	0.0088889	0.0111111	0.0000000
	6		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	7		0.1000000	0.0460000	0.0600000	0.0090000	0.0090000	0.0090000	0.0600000	0.0096000	0.0120000	0.0000000
	8		0.1000000	0.0460000	0.0600000	0.0090000	0.0090000	0.0090000	0.0600000	0.0096000	0.0120000	0.0000000
	9		0.1111111	0.0511111	0.0666667	0.0100000	0.0100000	0.0100000	0.0666667	0.0106667	0.0133333	0.0000000
	10		0.1000000	0.0460000	0.0500000	0.0075000	0.0075000	0.0075000	0.0500000	0.0080000	0.0100000	0.0000000
	11		0.0943396	0.0433962	0.0377358	0.0056604	0.0056604	0.0056604	0.0377358	0.0060377	0.0075472	0.0000000
	12		0.0909091	0.0418182	0.0545455	0.0081818	0.0081818	0.0081818	0.0545455	0.0087273	0.0109091	0.0000000
	13		0.1000000	0.0460000	0.0400000	0.0060000	0.0060000	0.0060000	0.0400000	0.0064000	0.0080000	0.0000000
	14		0.1111111	0.0511111	0.0555556	0.0083333	0.0083333	0.0083333	0.0555556	0.0088889	0.0111111	0.0000000
	15	**Wet Seeded**	0.0902527	0.0415162	0.0451264	0.0067690	0.0067690	0.0067690	0.0451264	0.0072202	0.0090253	0.0000000
	16	**Transplanting**	0.0806452	0.0370968	0.0403226	0.0060484	0.0060484	0.0060484	0.0403226	0.0064516	0.0080645	0.0000000
	17		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	18		0.0769231	0.0353846	0.0461538	0.0069231	0.0069231	0.0069231	0.0461538	0.0073846	0.0092308	0.0000000
	19		0.0909091	0.0418182	0.0545455	0.0081818	0.0081818	0.0081818	0.0545455	0.0087273	0.0109091	0.0000000
	20		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000

Application of fertilizers (Cont'd)

System			Irrigated wet season									
Commercial Name			Hua-Wua-Kun-Tai	46-0-0	Hua-Wua-Kun-Tai	15-15-15			Commercial Name	16-20-0		
Active Ingredient			Urea, as 46%N	N	15%N – 15%P_2O_5 – 15%K_2O	N	P	K	16%N – 20%P_2O_5 – 0%K_2O	N	P	K
DMU	**1**	**Dry seeded**	0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	2		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	3	**Wet Seeded**	0.0769231	0.0353846	0.0461538	0.0069231	0.0069231	0.0069231	0.0461538	0.0073846	0.0092308	0.0000000
	4		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	5		0.1000000	0.0460000	0.0500000	0.0075000	0.0075000	0.0075000	0.0500000	0.0080000	0.0100000	0.0000000
	6		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	7		0.0877193	0.0403509	0.0438596	0.0065789	0.0065789	0.0065789	0.0438596	0.0070175	0.0087719	0.0000000
	8		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	9		0.0909091	0.0418182	0.0363636	0.0054545	0.0054545	0.0054545	0.0363636	0.0058182	0.0072727	0.0000000
	10		0.0909091	0.0418182	0.0363636	0.0054545	0.0054545	0.0054545	0.0363636	0.0058182	0.0072727	0.0000000
	11		0.0862069	0.0396552	0.0344828	0.0051724	0.0051724	0.0051724	0.0344828	0.0055172	0.0068966	0.0000000
	12		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	13		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	14		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	15		0.0827815	0.0380795	0.0413907	0.0062086	0.0062086	0.0062086	0.0413907	0.0066225	0.0082781	0.0000000
	16		0.0746269	0.0343284	0.0447761	0.0067164	0.0067164	0.0067164	0.0447761	0.0071642	0.0089552	0.0000000
	17		0.0769231	0.0353846	0.0384615	0.0057692	0.0057692	0.0057692	0.0384615	0.0061538	0.0076923	0.0000000
	18	**Transplanting**	0.0769231	0.0353846	0.0384615	0.0057692	0.0057692	0.0057692	0.0384615	0.0061538	0.0076923	0.0000000
	19		0.0862069	0.0396552	0.0344828	0.0051724	0.0051724	0.0051724	0.0344828	0.0055172	0.0068966	0.0000000
	20		0.0833333	0.0383333	0.0333333	0.0050000	0.0050000	0.0050000	0.0333333	0.0053333	0.0066667	0.0000000

Application of fertilizers (Cont'd)

System			Irrigated dry season									
Commercial Name			Hua-Wua-Kun-Tai	46-0-0	Hua-Wua-Kun-Tai	15-15-15			Commercial Name	16-20-0		
Active Ingredient			Urea, as 46%N	N	15%N – 15%P_2O_5 – 15%K_2O	N	P	K	16%N – 20%P_2O_5 – 0%K_2O	N	P	K
DMU	**1**	**Dry seeded**	0.1000000	0.0460000	0.0500000	0.0075000	0.0075000	0.0075000	0.0500000	0.0080000	0.0100000	0.0000000
	2		0.0961538	0.0442308	0.0480769	0.0072115	0.0072115	0.0072115	0.0480769	0.0076923	0.0096154	0.0000000
	3		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	4		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	5		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	6	**Wet Seeded**	0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	7		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	8		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	9		0.1000000	0.0460000	0.0400000	0.0060000	0.0060000	0.0060000	0.0400000	0.0064000	0.0080000	0.0000000
	10		0.0909091	0.0418182	0.0363636	0.0054545	0.0054545	0.0054545	0.0363636	0.0058182	0.0072727	0.0000000
	11		0.0862069	0.0396552	0.0344828	0.0051724	0.0051724	0.0051724	0.0344828	0.0055172	0.0068966	0.0000000
	12		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	13		0.0909091	0.0418182	0.0454545	0.0068182	0.0068182	0.0068182	0.0454545	0.0072727	0.0090909	0.0000000
	14		0.1000000	0.0460000	0.0500000	0.0075000	0.0075000	0.0075000	0.0500000	0.0080000	0.0100000	0.0000000
	15		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	16		0.0909091	0.0418182	0.0545455	0.0081818	0.0081818	0.0081818	0.0545455	0.0087273	0.0109091	0.0000000
	17		0.0833333	0.0383333	0.0416667	0.0062500	0.0062500	0.0062500	0.0416667	0.0066667	0.0083333	0.0000000
	18	**Transplanting**	0.0877193	0.0403509	0.0438596	0.0065789	0.0065789	0.0065789	0.0438596	0.0070175	0.0087719	0.0000000
	19		0.0909091	0.0418182	0.0363636	0.0054545	0.0054545	0.0054545	0.0363636	0.0058182	0.0072727	0.0000000
	20		0.0877193	0.0403509	0.0350877	0.0052632	0.0052632	0.0052632	0.0350877	0.0056140	0.0070175	0.0000000

Application of pesticide

System			Rainfed			**System**			Irrigated dry season		
Pesticide product			Roundup	Polydon	R-S-5-G	**Pesticide product**			Roundup	Polydon	R-S-5-G
Active ingredient			Glyphosate	Calcium carbonate	Metaldehyde	**Active ingredient**			Glyphosate	Calcium carbonate	Metaldehyde
Associated chemical class in Ecoinvent			glyphosate	Calcium carbonate	Metaldehyde	**Associated chemical class in Ecoinvent**			glyphosate	Calcium carbonate	Metaldehyde
DMU	**1**	**Dry seeded**	0.0000909	0	0.0000556	**DMU**	**1**	**Dry seeded**	0.0000818	0	0.0000500
	2		0.0000786	0	0.0000481		**2**		0.0000786	0	0.0000481
	3		0.0000818	0	0.0000500		**3**		0.0000744	0	0.0000455
	4		0.0000744	0	0.0000455		**4**		0.0000744	0	0.0000455
	5		0.0000909	0	0.0000556		**5**		0.0000744	0	0.0000455
	6		0.0000744	0	0.0000455		**6**	**Wet Seeded**	0.0000682	0	0.0000417
	7		0.0000818	0	0.0000500		**7**		0.0000744	0	0.0000455
	8		0.0000818	0	0.0000500		**8**		0.0000744	0	0.0000455
	9		0.0000909	0	0.0000556		**9**		0.0000818	0	0.0000500
	10		0.0000818	0	0.0000000		**10**		0.0000744	0	0.0000455
	11		0.0000772	0	0.0000472		**11**		0.0000353	0	0.0000216
	12		0.0000744	0	0.0000455		**12**		0.0000682	0	0.0000417
	13		0.0000409	0	0.0000000		**13**		0.0000744	0	0.0000455
	14		0.0000909	0	0.0000556		**14**		0.0000818	0	0.0000500
	15	**Wet Seeded**	0.0000738	0	0.0000226		**15**		0.0000682	0	0.0000417
	16	**Transplanting**	0.0000660	0	0.0000403		**16**		0.0000744	0	0.0000455
	17		0.0000341	0	0.0000208		**17**		0.0000682	0	0.0000417
	18		0.0000629	0	0.0000385		**18**	**Transplanting**	0.0000717	0	0.0000439
	19		0.0000744	0	0.0000455		**19**		0.0000744	0	0.0000455
	20		0.0000744	0	0.0000455		**20**		0.0000717	0	0.0000439
System			Irrigated wet season								
DMU	**1**	**Dry seeded**	0.0000744	0	0.0000455	**DMU**	**11**	**Wet Seeded**	0.0000353	0	0.0000216
	2		0.0000744	0	0.0000455		**12**		0.0000682	0	0.0000417
	3	**Wet Seeded**	0.0000629	0	0.0000385		**13**		0.0000744	0	0.0000455
	4		0.0000682	0	0.0000417		**14**		0.0000744	0	0.0000455
	5		0.0000818	0	0.0000250		**15**		0.0000677	0	0.0000414
	6		0.0000682	0	0.0000417		**16**		0.0000610	0	0.0000373
	7		0.0000717	0	0.0000439		**17**		0.0000629	0	0.0000385
	8		0.0000744	0	0.0000455		**18**	**Transplanting**	0.0000629	0	0.0000385
	9		0.0000744	0	0.0000455		**19**		0.0000705	0	0.0000431
	10		0.0000744	0	0.0000455		**20**		0.0000682	0	0.0000417

Seeds application

System			Rainfed	System			Irr wet	System			Irr dry
DMU	**1**	**Dry seeded**	0.0333333	**DMU**	**1**	**Dry seeded**	0.036363636	**DMU**	**1**	**Dry seeded**	0.0400000
	2		0.0384615		**2**		0.036363636		**2**		0.0384615
	3		0.0400000		**3**	**Wet Seeded**	0.0307692		**3**		0.0363636
	4		0.0363636		**4**		0.0333333		**4**		0.0363636
	5		0.0333333		**5**		0.0300000		**5**		0.0363636
	6		0.0272727		**6**		0.0250000		**6**	**Wet Seeded**	0.0250000
	7		0.0400000		**7**		0.0350877		**7**		0.0363636
	8		0.0400000		**8**		0.0363636		**8**		0.0363636
	9		0.0444444		**9**		0.0363636		**9**		0.0400000
	10		0.0300000		**10**		0.0363636		**10**		0.0363636
	11		0.0377358		**11**		0.0344828		**11**		0.0344828
	12		0.0363636		**12**		0.0333333		**12**		0.0333333
	13		0.0400000		**13**		0.0363636		**13**		0.0363636
	14		0.0333333		**14**		0.0363636		**14**		0.0400000
	15	**Wet Seeded**	0.0361011		**15**		0.0331126		**15**		0.0333333
	16	**Transplanting**	0.0322581		**16**		0.0298507		**16**		0.0363636
	17		0.0333333		**17**		0.0307692		**17**		0.0333333
	18		0.0307692		**18**	**Transplanting**	0.0307692		**18**	**Transplanting**	0.0350877
	19		0.0272727		**19**		0.0344828		**19**		0.0363636
	20		0.0363636		**20**		0.0333333		**20**		0.0350877

Direct field emissions

System			Rainfed											
Direct emission			**Emission to air**				**Emission to water**					**Emission to soil**		
			Methane (CH_4)	**N_2O**	**NO**	**NH_3**	**Nitrates**	**Phosphorus**	**glyphosate**	**CaCo3**	**Metaldehyde**	**glyphosate**	**CaCo3**	**Metaldehyde**
Reference Unit			kg CH_4	kg N-N_2O	kg N-NO	kg N-NH_3	kg N	kg P	g	g	g	g	g	g
DMU	**1**	**Dry seeded**	0.084	0.000	0.000	0.019	0.033	0.015	0.045	0.000	0.028	0.045	0.000	0.028
	2		0.076	0.000	0.000	0.017	0.027	0.012	0.039	0.000	0.024	0.039	0.000	0.024
	3		0.078	0.000	0.000	0.017	0.031	0.016	0.041	0.000	0.025	0.041	0.000	0.025
	4		0.073	0.000	0.000	0.016	0.027	0.014	0.037	0.000	0.023	0.037	0.000	0.023
	5		0.084	0.000	0.000	0.019	0.033	0.015	0.045	0.000	0.028	0.045	0.000	0.028
	6		0.073	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	7		0.078	0.000	0.000	0.017	0.031	0.016	0.041	0.000	0.025	0.041	0.000	0.025
	8		0.078	0.000	0.000	0.017	0.031	0.016	0.041	0.000	0.025	0.041	0.000	0.025
	9		0.084	0.000	0.000	0.019	0.036	0.019	0.045	0.000	0.028	0.045	0.000	0.028
	10		0.078	0.000	0.000	0.017	0.029	0.013	0.041	0.000	0.000	0.041	0.000	0.000
	11		0.075	0.000	0.000	0.016	0.024	0.008	0.039	0.000	0.024	0.039	0.000	0.024
	12		0.073	0.000	0.000	0.016	0.027	0.014	0.037	0.000	0.023	0.037	0.000	0.023
	13		0.078	0.000	0.000	0.017	0.026	0.009	0.020	0.000	0.000	0.020	0.000	0.000
	14		0.084	0.000	0.000	0.019	0.033	0.015	0.045	0.000	0.028	0.045	0.000	0.028
	15	**Wet Seeded**	0.072	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.011	0.037	0.000	0.011
	16	**Transplanting**	0.067	0.000	0.000	0.014	0.021	0.009	0.033	0.000	0.020	0.033	0.000	0.020
	17		0.069	0.000	0.000	0.014	0.022	0.010	0.017	0.000	0.010	0.017	0.000	0.010
	18		0.065	0.000	0.000	0.013	0.021	0.011	0.031	0.000	0.019	0.031	0.000	0.019
	19		0.073	0.000	0.000	0.016	0.027	0.014	0.037	0.000	0.023	0.037	0.000	0.023
	20		0.073	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023

Direct field emissions (Cont'd)

System			Irr. Wet											
Direct emission			**Emission to air**				**Emission to water**					**Emission to soil**		
			Methane (CH_4)	**N_2O**	**NO**	**NH_3**	**Nitrates**	**Phosphorus**	**glyphosate**	**CaCo3**	**Metaldehyde**	**glyphosate**	**CaCo3**	**Metaldehyde**
Reference Unit			kg CH_4	kg N-N_2O	kg N-NO	kg N-NH_3	kg N	kg P	g	g	g	g	g	g
DMU	**1**	**Dry seeded**	0.107	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	2		0.107	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	3	**Wet Seeded**	0.095	0.000	0.000	0.013	0.021	0.011	0.031	0.000	0.019	0.031	0.000	0.019
	4		0.101	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	5		0.115	0.000	0.000	0.017	0.029	0.013	0.041	0.000	0.013	0.041	0.000	0.013
	6		0.101	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	7		0.104	0.000	0.000	0.015	0.024	0.010	0.036	0.000	0.022	0.036	0.000	0.022
	8		0.107	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	9		0.107	0.000	0.000	0.016	0.022	0.008	0.037	0.000	0.023	0.037	0.000	0.023
	10		0.107	0.000	0.000	0.016	0.022	0.008	0.037	0.000	0.023	0.037	0.000	0.023
	11		0.103	0.000	0.000	0.015	0.021	0.007	0.018	0.000	0.011	0.018	0.000	0.011
	12		0.101	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	13		0.107	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	14		0.107	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	15		0.100	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	16		0.093	0.000	0.000	0.013	0.020	0.011	0.031	0.000	0.019	0.031	0.000	0.019
	17		0.095	0.000	0.000	0.013	0.019	0.009	0.031	0.000	0.019	0.031	0.000	0.019
	18	**Transplanting**	0.095	0.000	0.000	0.013	0.019	0.009	0.031	0.000	0.019	0.031	0.000	0.019
	19		0.103	0.000	0.000	0.015	0.021	0.007	0.035	0.000	0.022	0.035	0.000	0.022
	20		0.101	0.000	0.000	0.014	0.019	0.007	0.034	0.000	0.021	0.034	0.000	0.021

Direct field emissions (Cont'd)

System			Irr. Dry											
Direct emission			**Emission to air**				**Emission to water**					**Emission to soil**		
			Methane (CH_4)	**N_2O**	**NO**	**NH_3**	**Nitrates**	**Phosphorus**	**glyphosate**	**CaCo3**	**Metaldehyde**	**glyphosate**	**CaCo3**	**Metaldehyde**
Reference Unit			kg CH_4	kg N-N_2O	kg N-NO	kg N-NH_3	kg N	kg P	g	g	g	g	g	g
DMU	**1**	**Dry seeded**	0.060	0.000	0.000	0.017	0.029	0.013	0.041	0.000	0.025	0.041	0.000	0.025
	2		0.058	0.000	0.000	0.017	0.027	0.012	0.039	0.000	0.024	0.039	0.000	0.024
	3		0.056	0.000	0.000	0.016	0.027	0.014	0.037	0.000	0.023	0.037	0.000	0.023
	4		0.056	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	5		0.060	0.000	0.000	0.017	0.029	0.013	0.037	0.000	0.023	0.037	0.000	0.023
	6	**Wet Seeded**	0.052	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	7		0.056	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	8		0.056	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	9		0.060	0.000	0.000	0.017	0.026	0.009	0.041	0.000	0.025	0.041	0.000	0.025
	10		0.056	0.000	0.000	0.016	0.022	0.008	0.037	0.000	0.023	0.037	0.000	0.023
	11		0.054	0.000	0.000	0.015	0.021	0.007	0.018	0.000	0.011	0.018	0.000	0.011
	12		0.052	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	13		0.056	0.000	0.000	0.016	0.025	0.011	0.037	0.000	0.023	0.037	0.000	0.023
	14		0.060	0.000	0.000	0.017	0.029	0.013	0.041	0.000	0.025	0.041	0.000	0.025
	15		0.052	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	16		0.056	0.000	0.000	0.016	0.027	0.014	0.037	0.000	0.023	0.037	0.000	0.023
	17		0.052	0.000	0.000	0.014	0.022	0.010	0.034	0.000	0.021	0.034	0.000	0.021
	18	**Transplanting**	0.054	0.000	0.000	0.015	0.024	0.010	0.036	0.000	0.022	0.036	0.000	0.022
	19		0.056	0.000	0.000	0.016	0.022	0.008	0.037	0.000	0.023	0.037	0.000	0.023
	20		0.054	0.000	0.000	0.015	0.021	0.007	0.036	0.000	0.022	0.036	0.000	0.022

Environmental impact performances

System			Rainfed							
Impact indicator			GWP$_{100}$	EP	AP	ODP	FWAE	WU	LU	EU
Reference unit			kg CO2-eq	kg PO4-eq	kg SO2-eq	mg CFC-11-eq	kg 1,4-DB eq	m^3	ha	MJ
DMU	**1**	**Dry seeded**	2.410	0.067	0.034	0.047	0.091	2.206	0.00036	6.592
	2		2.170	0.055	0.029	0.041	0.088	1.909	0.00031	5.849
	3		2.250	0.070	0.031	0.043	0.085	1.986	0.00032	6.338
	4		2.090	0.062	0.028	0.040	0.077	1.805	0.00029	5.811
	5		2.410	0.067	0.034	0.047	0.091	2.206	0.00036	6.643
	6		2.060	0.051	0.028	0.038	0.085	1.805	0.00029	5.462
	7		2.250	0.070	0.031	0.043	0.085	1.986	0.00032	6.317
	8		2.250	0.070	0.031	0.043	0.085	1.986	0.00032	6.423
	9		2.440	0.080	0.034	0.048	0.094	2.206	0.00036	7.039
	10		2.220	0.058	0.030	0.042	0.082	1.986	0.00032	5.796
	11		2.130	0.042	0.028	0.040	0.077	1.873	0.00030	5.485
	12		2.090	0.062	0.028	0.030	0.077	1.805	0.00029	5.742
	13		2.220	0.046	0.030	0.042	0.053	1.986	0.00032	5.439
	14		2.410	0.067	0.034	0.047	0.091	2.206	0.00036	6.612
	15	**Wet Seeded**	2.300	0.051	0.029	0.046	0.140	2.659	0.00029	5.534
	16	**Transplanting**	2.210	0.043	0.026	0.042	0.128	2.807	0.00027	5.360
	17		2.170	0.046	0.027	0.049	0.109	2.901	0.00028	5.373
	18		2.050	0.050	0.025	0.040	0.124	2.678	0.00026	5.398
	19		2.320	0.062	0.030	0.047	0.145	3.164	0.00031	6.238
	20		2.330	0.051	0.029	0.047	0.145	3.164	0.00031	6.153

Environmental impact performances (Cont’d)

System			Irr. Wet							
Impact indicator			GWP_{100}	EP	AP	ODP	FWAE	WU	LU	EU
Reference unit			kg CO2-eq	kg PO4-eq	kg SO2-eq	mg CFC-11-eq	kg 1,4-DB eq	m^3	ha	MJ
DMU	**1**	**Dry seeded**	2.870	0.051	0.028	0.039	0.076	1.805	0.00029	5.569
	2		2.870	0.051	0.028	0.039	0.076	1.8050437	0.00029	5.574
	3	**Wet Seeded**	2.740	0.050	0.025	0.039	0.121	2.266	0.00025	4.948
	4		2.900	0.045	0.027	0.042	0.129	2.455	0.00027	5.123
	5		3.320	0.059	0.032	0.050	0.153	2.946	0.00032	6.131
	6		2.890	0.045	0.027	0.041	0.128	2.455	0.00027	5.019
	7		3.010	0.049	0.028	0.044	0.126	2.584	0.00028	5.305
	8		3.100	0.051	0.029	0.046	0.141	2.678	0.00029	5.480
	9		3.080	0.040	0.029	0.045	0.139	2.678	0.00029	5.337
	10		3.080	0.040	0.029	0.045	0.139	2.678	0.00029	5.337
	11		2.960	0.037	0.027	0.043	0.108	2.539	0.00028	5.081
	12		2.900	0.045	0.027	0.042	0.129	2.455	0.00027	5.039
	13		3.100	0.051	0.029	0.046	0.141	2.678	0.00029	5.552
	14		3.100	0.051	0.029	0.046	0.141	2.678	0.00029	5.552
	15		2.880	0.045	0.027	0.042	0.128	2.439	0.00026	5.076
	16		2.680	0.048	0.024	0.038	0.117	2.198	0.00024	4.766
	17		2.730	0.040	0.025	0.039	0.119	2.266	0.00025	4.729
	18	**Transplanting**	2.740	0.040	0.025	0.040	0.122	2.668	0.00026	4.957
	19		2.970	0.037	0.027	0.044	0.134	2.986	0.00029	5.296
	20		2.900	0.035	0.026	0.042	0.130	2.886	0.00028	5.120

Environmental impact performances (Cont’d)

System			Irr. Wet							
Impact indicator			GWP_{100}	EP	AP	ODP	FWAE	WU	LU	EU
Reference unit			kg CO2-eq	kg PO4-eq	kg SO2-eq	mg CFC-11-eq	kg 1,4-DB eq	m^3	ha	MJ
DMU	**1**	**Dry seeded**	2.150	0.059	0.033	0.053	0.178	2.144	0.00032	6.126
	2		2.080	0.056	0.031	0.051	0.172	2.061	0.00031	5.896
	3		1.990	0.062	0.030	0.048	0.162	1.949	0.00029	5.800
	4		1.990	0.052	0.030	0.048	0.162	1.949	0.00029	5.610
	5		2.130	0.059	0.032	0.050	0.176	2.144	0.00032	6.173
	6	**Wet Seeded**	2.050	0.046	0.029	0.049	0.207	2.587	0.00027	5.019
	7		2.220	0.052	0.031	0.055	0.228	2.822	0.00029	5.498
	8		2.220	0.052	0.031	0.055	0.228	2.822	0.00029	5.480
	9		2.390	0.047	0.034	0.060	0.249	3.104	0.00032	5.870
	10		2.210	0.041	0.031	0.052	0.226	2.822	0.00029	5.337
	11		2.110	0.038	0.029	0.051	0.190	2.676	0.00028	5.081
	12		2.070	0.046	0.029	0.050	0.209	2.587	0.00027	5.039
	13		2.220	0.052	0.031	0.055	0.228	2.822	0.00029	5.552
	14		2.400	0.059	0.034	0.060	0.250	3.104	0.00032	6.107
	15		2.070	0.046	0.029	0.050	0.209	2.587	0.00027	5.109
	16		2.230	0.629	0.315	0.055	0.229	2.822	0.00029	5.806
	17		2.070	0.046	0.029	0.050	0.209	2.587	0.00027	5.123
	18	**Transplanting**	2.160	0.049	0.030	0.054	0.221	2.899	0.00029	5.652
	19		2.210	0.041	0.031	0.055	0.227	3.000	0.00030	5.585
	20		2.150	0.039	0.030	0.053	0.219	2.894	0.00029	5.389

APPENDIX D

ECO-EFFICIENCY ANALYSIS

Table D-1 Eco-efficiency (gross income per environmental impact, as per category) of Nam Mae Lao basin – year 2010

Impact indicator	Reference unit	Eco-Efficiency								
		Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
		Baht/Ref. Unit								
GWP$_{100}$	**kg CO$_2$-eq**	5.854	5.369	4.918	4.478	4.138	3.614	6.030	5.581	5.000
EP	**kg PO$_4$-eq**	283.019	199.867	149.254	338.983	264.317	204.778	317.460	237.962	19.078
AP	**kg SO$_2$-eq**	478.088	407.481	350.877	495.868	438.758	375.000	421.053	389.610	38.095
ODP	**mg CFC-11-eq**	406.780	276.498	243.902	316.623	285.378	242.424	250.522	228.356	199.667
FAETP	**kg 1,4-DB eq**	225.564	134.249	82.759	158.940	93.387	78.431	74.074	56.105	48.000
WU	**m3**	6.648	5.741	3.792	6.648	4.685	4.019	6.157	4.369	3.866
LU	**ha**	46,313	39,094	33,750	50,250	43,125	37,500	45,000	41,250	37,500
EU	**MJ**	2.239	2.058	1.705	2.537	2.304	1.957	2.391	2.155	1.944

Table D-2 Net income per environmental impact (as per category) of Nam Mae Lao basin – year 2010

Impact indicator	Reference unit	Net return to environmental impact								
		Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
		Baht/Ref. Unit								
GWP$_{100}$	**kg CO$_2$-eq**	3.038	2.321	1.432	2.323	1.993	1.431	2.874	2.591	1.920
EP	**kg PO$_4$-eq**	144.789	84.759	43.447	175.553	127.463	81.090	160.433	103.668	7.741
AP	**kg SO$_2$-eq**	248.110	175.664	102.138	257.700	216.078	148.496	207.684	174.874	15.457
ODP	**mg CFC-11-eq**	168.193	119.658	72.471	160.573	137.663	95.998	118.214	105.861	76.661
FAETP	**kg 1,4-DB eq**	102.913	50.893	35.673	70.209	45.034	31.058	32.298	26.627	18.429
WU	**m3**	2.930	2.192	1.583	2.937	2.350	1.613	2.665	2.111	1.484
LU	**Ha**	24,034	16,944	9,824	25,484	21,355	14,850	21,983	18,086	14,398
EU	**MJ**	1.176	0.857	0.496	1.311	1.131	0.775	1.193	0.959	0.754

Table D-3 Eco-efficiency (gross income per environmental impact, as per category) of Lam Sieo Yai basin – year 2010

Impact indicator	**Reference unit**	**Eco-Efficiency**								
		Rain-fed			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		Baht/Ref. Unit								
GWP$_{100}$	**kg CO$_2$-eq**	4.225	4.040	3.478	2.661	2.464	2.344	2.37	2.16	1.935
EP	**kg PO$_4$-eq**	170.455	159.787	128.894	175.182	151.707	138.408	142.69	121.09	100.840
AP	**kg SO$_2$-eq**	289.157	275.229	231.660	332.410	297.030	275.862	281.69	246.41	211.268
ODP	**mg CFC-11-eq**	179.910	169.972	143.027	198.020	177.515	164.384	167.13	146.16	124.870
FAETP	**kg 1,4-DB eq**	45.977	43.636	36.697	44.610	39.867	37.037	37.15	32.52	27.907
WU	**m3**	4.766	4.534	3.806	5.010	4.484	4.157	4.135	3.62	3.10
LU	**ha**	30,000	28,500	24,000	35,250	31,500	29,250	30,000	26,250	22,500
EU	**MJ**	1.729	1.647	1.374	1.808	1.600	1.477	1.505	1.25	1.22

Table D-4 Net income per environmental impact (as per category) of Lam Sieo Yai basin – year 2010

Impact indicator	**Reference unit**	**Net return to environmental impact**								
		Rain-fed			**Wet-season irrigated rice**			**Dry-season irrigated rice**		
		Max.	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**
		Baht/Ref. Unit								
GWP$_{100}$	**kg CO$_2$-eq**	1.577	1.356	0.751	1.159	0.901	0.736	0.799	0.439	0.225
EP	**kg PO$_4$-eq**	63.978	53.694	27.862	75.787	55.556	43.340	48.106	24.583	11.724
AP	**kg SO$_2$-eq**	106.631	91.523	49.830	145.259	109.723	85.694	93.975	49.667	24.476
ODP	**mg CFC-11-eq**	66.843	56.719	30.847	85.726	64.543	51.651	56.124	29.679	14.532
FAETP	**kg 1,4-DB eq**	17.159	14.591	7.876	19.440	14.485	11.602	12.511	6.560	3.237
WU	**m3**	1.779	1.522	0.822	2.183	1.640	1.306	1.392	0.734	0.360
LU	**Ha**	11,196	9,588	5,182	15,380	11,550	9,196	10,102	5,291	2,632
EU	**MJ**	0.648	0.555	0.299	0.792	0.590	0.469	0.511	0.255	0.143

APPENDIX E

TECHNICAL AND ENVIRONMENTAL EFFICIENCIES ANALYSIS

Table E-1 Variables inputs and output for technical efficiency assessment of Nam Mae Lao Basin

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Baht /ha)**			**Variable output**
			Fertilizer	**Pesticide**	**Machinery**	**Net income (Baht/ha)**
1	**Rainfed**	**dry seeding**	12,188	1,719	6,972	11,100
2			12,188	1,719	6,969	16,049
3			13,375	1,719	6,967	13,489
4			13,375	1,719	7,055	16,996
5			12,188	1,719	7,054	11,084
6			12,188	1,719	7,055	18,183
7			13,375	1,719	6,972	13,484
8			13,375	1,719	6,981	13,475
9			13,375	1,719	6,970	9,824
10			12,188	938	7,055	15,755
11			11,000	1,719	6,966	18,041
12			13,375	1,719	6,972	17,056
13			11,000	469	6,972	17,109
14			12,188	1,719	6,970	13,690
15		**wet seeding**	12,188	1,328	7,112	18,944
16		**transplanting**	12,188	1,719	7,300	23,079
17			12,188	859	7,300	22,510
18			13,375	1,719	7,300	24,034
19			13,375	1,719	7,300	16,892
20			12,188	1,719	7,300	18,079
-		**Maximum**	**13,375**	**1,719**	**7,300**	**24,034**
-		**Median**	**12,188**	**1,719**	**7,017**	**16,944**
-		**Minimum**	**11,000**	**469**	**6,966**	**9,824**
21	**wet season irrigated**	**dry seeding**	12,188	1,719	7,068	18,221
22			12,188	1,719	7,068	18,212
23		**wet seeding**	13,375	1,719	7,311	24,024
24			12,188	1,719	7,340	21,611
25			12,188	1,328	7,349	14,850
26			12,188	1,719	7,292	21,658
27			12,188	1,719	7,204	19,604
28			12,188	1,719	7,192	18,188
29			11,000	1,719	7,255	19,312
30			11,000	1,719	7,255	19,312
31			11,000	859	7,349	22,220
32			12,188	1,719	7,208	21,743
33			12,188	1,719	7,255	18,125
34			12,188	1,719	7,255	18,125
35			12,188	1,719	7,349	21,888
36			13,375	1,719	7,279	25,484
37			12,188	1,719	7,340	25,183
38		**transplanting**	12,188	1,719	7,646	24,877
39			11,000	1,719	7,611	21,099
40			11,000	1,719	7,611	22,528
-		**Maximum**	**13,375**	**1,719**	**7,646**	**25,484**
-		**Median**	**12,188**	**1,719**	**7,286**	**21,355**
-		**Minimum**	**11,000**	**859**	**7,068**	**14,850**

DMU	Rice cropping system	Methods	Variable inputs (Baht /ha)			Variable output
			Fertilizer	Pesticide	Machinery	Net income (Baht/ha)
41	**dry season irrigated**	**dry seeding**	12,188	1,719	7,241	14,478
42			12,188	1,719	7,211	15,927
43			12,188	1,719	7,380	17,855
44			12,188	1,719	7,570	17,645
45			12,188	1,719	7,616	17,764
46		**wet seeding**	12,188	1,719	7,482	21,469
47			12,188	1,719	7,306	18,073
48			12,188	1,719	7,281	18,099
49			11,000	1,719	7,410	15,585
50			11,000	1,719	7,410	19,157
51			11,000	859	7,586	21,983
52			12,188	1,719	7,313	21,637
53			12,188	1,719	7,410	17,969
54			12,188	1,719	7,410	14,398
55			12,188	1,719	7,586	21,365
56			13,375	1,719	7,455	16,737
57			12,188	1,719	7,577	21,374
58		**transplanting**	12,188	1,719	7,488	19,320
59			11,000	1,719	7,462	19,105
60			11,000	1,719	7,462	20,534
-		**Maximum**	**13,375**	**1,719**	**7,616**	**21,983**
-		**Median**	**12,188**	**1,719**	**7,432**	**18,086**
-		**Minimum**	**11,000**	**859**	**7,211**	**14,398**

Table E-2 TE analysis, as per rice cropping systems of Nam Mae Lao basin

DMU	Rice cropping system	Methods	Technical efficiencies score		
			CRS	VRS	SC
1	**Rainfed**	**dry seeding**	0.4594	0.9992	0.4598
2			0.6645	0.9996	0.6647
3			0.5530	0.9999	0.5531
4			0.6881	0.9874	0.6969
5			0.4545	0.9876	0.4602
6			0.7454	0.9883	0.7542
7			0.5525	0.9992	0.5529
8			0.5514	0.9979	0.5525
9			0.4026	0.9995	0.4028
10			0.7119	0.9880	0.7206
11			0.7937	1.0	0.7937
12			0.6988	0.9992	0.6994
13			1.0	1.0	1.0000
14			0.5668	0.9995	0.5670
15		**wet seeding**	0.8050	0.9869	0.8157
16		**transplanting**	0.9205	0.9885	0.9311
17			1.0	1.0	1.0
18			0.9415	0.9889	0.9521
19			0.6617	0.9543	0.6934
20			0.7211	0.9548	0.7552

Table E-2 TE analysis, as per rice cropping systems of Nam Mae Lao basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Technical efficiencies score**		
			CRS	**VRS**	**SC**
-	**Rainfed**	**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.6935**	**0.9985**	**0.6981**
-		**Minimum**	**0.4026**	**0.9543**	**0.4028**
21	**wet season irrigated**	**dry seeding**	0.7459	0.9867	0.7559
22			0.7455	0.9867	0.7556
23		**wet seeding**	0.9403	0.9874	0.9522
24			0.8582	0.9725	0.8824
25			0.6176	0.9482	0.6514
26			0.8646	0.9785	0.8836
27			0.7902	0.9763	0.8095
28			0.7342	0.9698	0.7571
29			0.8497	1.0	0.8497
30			0.8497	1.0	0.8497
31			1.0	1.0	1.0
32			0.8761	0.9893	0.8856
33			0.7265	0.9610	0.7560
34			0.7265	0.9610	0.7560
35			0.8692	0.9736	0.8928
36			1.0	1.0	1.0
37			1.0	1.0	1.0
38		**transplanting**	0.9879	0.9890	0.9988
39			0.9283	1.0	0.9283
40			0.9912	1.0	0.9912
-		**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.8614**	**0.9871**	**0.8830**
-		**Minimum**	**0.6176**	**0.9482**	**0.6514**
41	**dry season irrigated**	**dry seeding**	0.5813	0.9621	0.6041
42			0.6416	0.9661	0.6641
43			0.7090	0.9439	0.7512
44			0.7007	0.9203	0.7613
45			0.7054	0.9148	0.7711
46		**wet seeding**	0.8525	0.9550	0.8927
47			0.7204	0.9541	0.7551
48			0.7234	0.9575	0.7555
49			0.6857	1.0	0.6857
50			0.8428	1.0	0.8428
51			0.9893	1.0	0.9893
52			0.8617	0.9758	0.8831
53			0.7136	0.9402	0.7590
54			0.5717	0.9402	0.6081
55			0.8484	0.9432	0.8995
56			0.6473	0.9345	0.6926
57			0.8488	0.9442	0.8989
58		**transplanting**	0.7672	0.9380	0.8179
59			0.8406	1.0	0.8406
60			0.9034	1.0	0.9034
-		**Maximum**	**0.9893**	**1.0000**	**0.9893**
-		**Median**	**0.7219**	**0.9545**	**0.7662**
-		**Minimum**	**0.5717**	**0.9148**	**0.6041**

Table E-3 Target quantities and potential reduction by CRS model of Technical performance of Nam Mae Lao basin

Rice cropping system	Methods	Cost of fertilizer			Cost of pesticide			Cost of machinery		
		Target	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**
Rainfed	**dry seeding**	5,599	6,588	54.06	753	966	56.18	3,203	3,769	54.06
		8,098	4,089	33.55	1,089	630	36.65	4,630	2,338	33.55
		7,080	6,295	47.07	910	809	47.07	3,853	3,114	44.70
		8,920	4,455	33.31	1,146	572	33.31	4,855	2,200	31.19
		5,539	6,648	54.55	753	966	56.19	3,206	3,848	54.55
		9,085	3,103	25.46	1,235	483	28.12	5,259	1,796	25.46
		7,077	6,298	47.09	909	809	47.09	3,852	3,120	44.75
		7,072	6,303	47.12	909	810	47.12	3,849	3,132	44.86
		5,156	8,219	61.45	663	1,056	61.45	2,806	4,163	59.74
		8,493	3,695	30.32	667	270	28.81	5,022	2,032	28.81
		8,731	2,269	20.63	1,231	487	28.36	5,258	1,708	24.52
		8,952	4,423	33.07	1,150	568	33.07	4,872	2,100	30.12
		11,000	0	0	469	0	0	6,972	0	0
		6,907	5,280	43.32	929	790	45.96	3,950	3,019	43.32
	wet seeding	9,811	2,377	19.50	1,069	259	19.50	5,725	1,387	19.50
	transplanting	11,218	969	7.95	1,574	145	8.41	6,720	581	7.95
		12,188	0	0	859	0	0	7,300	0	0
		12,592	783	5.85	1,618	101	5.85	6,873	427	5.85
		8,850	4,525	33.83	1,137	581	33.83	4,830	2,470	33.83
		8,788	3,400	27.89	1,233	486	28.25	5,264	2,036	27.89
	Maximum	**12,592**	**8,219**	**61.45**	**1,618**	**1,056**	**61.45**	**7300.33**	**4163.34**	**59.74**
	Median	**8,759**	**4,256**	**33.19**	**999**	**570**	**33.19**	**4863.36**	**2150.13**	**30.65**
	Minimum	**5,156**	**0**	**0**	**469**	**0**	**0**	**2,806**	**0**	**0**

Table E-3 Target quantities and potential reduction by CRS model of Technical performance of Nam Mae Lao basin (Cont'd)

Rice cropping system	**Methods**	**Cost of fertilizer**			**Cost of pesticide**			**Cost of machinery**		
		Target	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**
wet season irrigated	**dry seeding**	9,090	3,097	25.41	1,238	480	27.96	5,272	1,796	25.41
		9,086	3,102	25.45	1,238	481	27.99	5,270	1,799	25.45
	wet seeding	12,576	799	5.97	1,616	103	5.97	6,874	437	5.97
		10,459	1,728	14.18	1,475	244	14.18	6,299	1,041	14.18
		7,528	4,660	38.24	820	508	38.24	4,539	2,810	38.24
		10,537	1,651	13.54	1,477	242	14.06	6,305	988	13.54
		9,631	2,556	20.98	1,335	384	22.32	5,693	1,511	20.98
		8,948	3,239	26.58	1,238	480	27.94	5,280	1,911	26.58
		9,346	1,654	15.03	1,318	401	23.31	5,629	1,626	22.41
		9,346	1,654	15.03	1,318	401	23.31	5,629	1,626	22.41
		11,000	0	0	859	0	0	7,349	0	0
		10,678	1,510	12.39	1,481	238	13.84	6,315	893	12.39
		8,854	3,333	27.35	1,235	483	28.12	5,271	1,984	27.35
		8,854	3,333	27.35	1,235	483	28.12	5,271	1,984	27.35
		10,593	1,595	13.08	1,494	225	13.08	6,379	970	13.19
		13,375	0	0	1,719	0	0	7,279	0	0
		12,188	0	0	1,719	0	0	7,340	0	0
	transplanting	12,039	148	1.21	1,698	21	1.21	7,251	395	5.17
		10,211	789	7.17	1,440	279	16.21	6,150	1,461	19.20
		10,903	97	0.88	1,538	181	10.54	6,566	1,045	13.72
	Maximum	**13,375**	**4,660**	**38.24**	**1,719**	**508**	**38.24**	**7349.01**	**2809.92**	**38.24**
	Median	**10,335**	**1,652**	**13.86**	**1,388**	**261**	**15.20**	**6224.27**	**1252.69**	**16.69**
	Minimum	**7,528**	**0**	**0**	**820**	**0**	**0**	**4,539**	**0**	**0**

Table E-3 Target quantities and potential reduction by CRS model of Technical performance of Nam Mae Lao basin (Cont'd)

Rice cropping system	**Methods**	**Cost of fertilizer**			**Cost of pesticide**			**Cost of machinery**		
		Target	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**
dry season irrigated	**dry seeding**	7,084	5,103	41.87	987	732	42.60	4,209	3,032	41.87
		7,820	4,368	35.84	1,085	634	36.88	4,626	2,584	35.84
		8,641	3,546	29.10	1,219	500	29.10	5,204	2,176	29.49
		8,540	3,648	29.93	1,204	514	29.93	5,143	2,427	32.06
		8,597	3,590	29.46	1,212	506	29.46	5,177	2,438	32.02
	wet seeding	10,390	1,797	14.75	1,465	253	14.75	6,257	1,224	16.37
		8,780	3,408	27.96	1,233	486	28.27	5,263	2,043	27.96
		8,817	3,371	27.66	1,234	485	28.20	5,267	2,014	27.66
		7,543	3,457	31.43	1,064	655	38.11	4,543	2,868	38.70
		9,271	1,729	15.72	1,307	411	23.93	5,584	1,827	24.65
		10,883	117	1.07	850	9	1.07	7,271	315	4.15
		10,502	1,685	13.83	1,476	243	14.11	6,302	1,011	13.83
		8,697	3,491	28.64	1,226	492	28.64	5,237	2,173	29.32
		6,968	5,219	42.83	983	736	42.83	4,196	3,214	43.37
		10,340	1,848	15.16	1,458	261	15.16	6,227	1,359	17.91
		8,657	4,718	35.27	1,112	606	35.27	4,825	2,630	35.27
		10,344	1,843	15.12	1,459	260	15.12	6,230	1,347	17.78
	transplanting	9,350	2,837	23.28	1,319	400	23.28	5,631	1,857	24.80
		9,246	1,754	15.94	1,304	415	24.13	5,568	1,893	25.37
		9,938	1,062	9.66	1,401	317	18.46	5,985	1,477	19.79
	Maximum	**10,883**	**5,219**	**42.83**	**1,476**	**736**	**42.83**	**7270.68**	**3213.66**	**43.37**
	Median	**8,798**	**3,389**	**27.81**	**1,230**	**485**	**28.23**	**5265.05**	**2028.23**	**27.81**
	Minimum	**6,968**	**117**	**1.07**	**850**	**9.16**	**1.07**	**4196.47**	**315.17**	**4.15**

Table E-4 Variables inputs and output for technical efficiency assessment of Lam Sieo Yai Basin

DMU	Rice cropping system	Methods	Variable inputs (baht/ha)			Variable output
			Fertilizer	Pesticide	Machinery	Net income (Baht/ha)
1	**Rainfed**	**dry seeding**	12,188	1,590	7,091	7,650
2			12,188	1,500	7,181	6,227
3			12,188	1,500	7,156	9,564
4			12,188	1,590	7,066	10,090
5			12,188	1,590	7,091	8,756
6			12,188	1,500	7,135	6,273
7			12,188	1,590	7,066	5,678
8			12,188	1,500	7,156	6,500
9			12,188	1,590	7,066	8,900
10			12,188	1,590	7,045	9,564
11			12,188	1,837	6,818	9,564
12			12,188	1,837	6,818	9,564
13			12,188	1,590	7,045	5,182
14			12,188	1,590	7,066	9,564
15			12,188	1,500	7,181	9,564
16		**transplanting**	12,188	1,500	7,156	10,120
17			12,188	1,590	7,045	11,196
18			12,188	1,500	7,156	10,050
19		**wet seeding**	12,188	1,837	6,818	9,564
20			12,188	1,590	7,066	9,870
-		**Maximum**	**12,188**	**1,837**	**7,181**	**11,196**
-		**Median**	**12,188**	**1,590**	**7,066**	**9,564**
-		**Minimum**	**12,188**	**1,500**	**6,818**	**5,182**
21	**wet season irrigated**	**dry seeding**	13,375	2,656	6,323	9,193
22			13,375	2,656	6,323	11,550
23			13,375	2,656	6,323	11,510
24			13,375	2,656	6,323	9,870
25			13,375	2,656	6,323	11,158
26			13,375	2,656	6,323	11,500
27			13,375	2,656	6,323	10,035
28			13,375	2,307	6,672	11,520
29			13,375	2,665	6,314	12,000
30			13,375	2,656	6,323	11,521
31			13,375	2,307	6,672	11,000
32			13,375	2,665	6,314	11,230
33			13,375	2,656	6,323	10,800
34			13,375	2,665	6,314	11,750
35			13,375	2,307	6,753	11,521
36		**transplanting**	13,375	2,656	6,404	15,364
37			13,375	2,307	6,753	13,400
38			13,375	2,656	6,212	14,530

Table E-4 Variables inputs and output for technical efficiency assessment of Lam Sieo Yai Basin (Cont'd)

DMU	Rice cropping system	Methods	Variable inputs (baht/ha)			Variable output
			Fertilizer	Pesticide	Machinery	Net income (Baht/ha)
39	**wet season irrigated**	**wet seeding**	13,375	2,656	6,212	12,400
40			13,375	2,656	6,212	13,000
-		**Maximum**	**13,375**	**2,665**	**6,753**	**15,364**
-		**Median**	**13,375**	**2,656**	**6,323**	**11,521**
-		**Minimum**	**13,375**	**2,307**	**6,212**	**9,193**
41	**dry season irrigated**	**dry seeding**	13,375	3,281	6,287	6,585
42			13,375	3,281	6,287	6,157
43			13,375	3,281	6,287	5,157
44			13,375	3,281	6,287	4,157
45			13,375	3,281	6,287	4,157
46			13,375	3,281	6,287	2,616
47			13,375	3,281	6,287	5,325
48			13,375	3,125	4,228	3,307
49			13,375	3,281	4,228	3,300
50			13,375	3,281	4,894	5,325
51			13,375	3,281	4,894	3,500
52			13,375	3,125	4,384	3,125
53			13,375	3,281	6,287	5,325
54		**wet seeding**	13,375	3,281	6,759	8,750
55			13,375	3,125	6,915	6,157
56			13,375	3,281	6,443	7,800
57			13,375	3,281	6,287	8,990
58		**transplanting**	13,375	3,125	6,287	10,102
59			13,375	3,125	6,287	10,050
60			13,375	3,125	6,443	10,000
-		**Maximum**	**13,375**	**3,281**	**6,915**	**10,102**
-		**Median**	**13,375**	**3,281**	**6,287**	**5,325**
-		**Minimum**	**13,375**	**3,125**	**4,228**	**2,616**

Table E-5 TE analysis, as per rice cropping systems of Lam Sieo Yai basin

DMU	Rice cropping system	Methods	Technical efficiencies score		
			CRS	**VRS**	**SC**
1	**Rainfed**	**dry seeding**	0.6833	1.0	0.6833
2			0.5895	1.0	0.5895
3			0.9054	1.0	0.9054
4			0.9012	1.0	0.9012
5			0.7821	1.0	0.7821
6			0.5938	1.0	0.5938
7			0.5071	1.0	0.5071
8			0.6153	1.0	0.6153
9			0.7949	1.0	0.7949
10			0.8542	1.0	0.8542
11			0.7950	1.0	0.7950
12			0.7950	1.0	0.7950
13			0.4628	1.0	0.46
14			0.8542	1.0	0.8542
15			0.9054	1.0	0.9054
16		**transplanting**	0.9580	1.0	0.9580
17			1.0	1.0	1.0
18			0.9514	1.0	0.9514
19		**wet seeding**	0.7950	1.0	0.7950
20			0.8816	1.0	0.8816
-		**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.7950**	**1.0000**	**0.7950**
-		**Minimum**	**0.4628**	**1.0000**	**0.4628**
21	**wet season irrigated**	**dry seeding**	0.6060	0.9528	0.6360
22			0.7614	0.9715	0.7838
23			0.7588	0.9711	0.7813
24			0.6506	0.9582	0.6791
25			0.7355	0.9684	0.7596
26			0.7581	0.9711	0.7807
27			0.6615	0.9595	0.6895
28			0.8209	0.9563	0.8584
29			0.7922	0.9754	0.8122
30			0.7595	0.9712	0.7820
31			0.7838	0.9522	1.0
32			0.7414	0.9693	0.7648
33			0.7119	0.9655	0.7374
34			0.7757	0.9734	0.7969
35			0.8180	0.9529	0.8585
36		**transplanting**	1.0	1.0	1.0
37			0.9514	0.9729	1.0
38			0.9749	1.0000	0.9749
39		**wet seeding**	0.8320	0.9831	0.8464
40			0.8723	0.9878	0.8830
-		**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.7685**	**0.9711**	**0.7903**
-		**Minimum**	**0.6060**	**0.9522**	**0.6360**

Table E-5 TE analysis, as per rice cropping systems of Lam Sieo Yai basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Technical efficiencies score**		
			CRS	**VRS**	**SC**
41	**dry season irrigated**	**dry seeding**	0.4366	0.9419	0.4635
42			0.4082	0.9419	0.4334
43			0.3419	0.9419	0.3630
44			0.2756	0.9419	0.2926
45			0.2756	0.9419	0.2926
46			0.1734	0.9419	0.1841
47			0.3530	0.9419	0.3748
48			0.3260	1.0	0.3260
49			0.3253	1.0	0.3253
50			0.4535	1.0	0.4603
51			0.2981	1.0	0.3040
52			0.2971	0.9953	0.2985
53			0.3530	0.9419	0.3748
54		**wet seeding**	0.5695	0.9321	0.6110
55			0.4007	0.9255	0.4330
56			0.5077	0.9384	0.5410
57			0.5960	0.9527	0.6256
58		**transplanting**	0.6697	0.9615	0.6965
59			0.6663	1.0	0.6932
60			0.6509	1.0	0.6822
-		**Maximum**	**0.6697**	**1.0000**	**0.6965**
-		**Median**	**0.3769**	**0.9419**	**0.4039**
-		**Minimum**	**0.1734**	**0.9255**	**0.1841**

Table E-6 Target quantities and potential reduction by CRS model of Technical performance of Lam Sieo Yai basin

DMU	**Rice cropping system**	**Methods**	**Cost of fertilizer**			**Cost of pesticide**			**Cost of machinery**		
			Target	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**
1	**Rainfed**	**dry seeding**	8,327	3,860	31.67	1,086	504	31.67	4,814	2,277	32.12
2			6,778	5,409	44.38	884	616	41.05	3,918	3,262	45.43
3			10,411	1,777	14.58	1,358	142	9.46	6,018	1,138	15.90
4			10,984	1,204	9.88	1,433	157	9.88	6,349	717	10.15
5			9,531	2,656	21.79	1,243	346	21.79	5,509	1,581	22.30
6			6,829	5,359	43.97	891	609	40.62	3,947	3,187	44.68
7			6,181	6,007	49.29	806	784	49.29	3,573	3,493	49.44
8			7,076	5,112	41.94	923	577	38.47	4,090	3,066	42.84
9			9,688	2,499	20.51	1,264	326	20.51	5,600	1,466	20.74
10			10,411	1,777	14.58	1,358	232	14.58	6,018	1,027	14.58
11			9,689	2,499	20.50	1,460	377	20.50	5,314	1,504	22.06
12			9,689	2,499	20.50	1,460	377	20.50	5,314	1,504	22.06
13			5,641	6,547	54	736	854	54	3,261	3,784	54
14			10,411	1,777	14.58	1,358	232	14.58	6,018	1,048	14.83
15			10,411	1,777	14.58	1,358	142	9.46	6,018	1,163	16.19
16		**transplanting**	11,016	1,171	9.61	1,437	63	4.20	6,368	788	11.01
17			12,188	0	0	1,590	0	0	7,045	0	0
18			10,940	1,247	10.24	1,427	73	4.86	6,324	832	11.63
19		**wet seeding**	9,689	2,499	20.50	1,460	377	20.50	5,314	1,504	22.06
20			10,744	1,443	11.84	1,402	188	11.84	6,210	855	12.11
-		**Maximum**	**12,188**	**6,547**	**53.72**	**1,590**	**854**	**53.72**	**7,045**	**3,784**	**53.72**
-		**Median**	**9,689**	**2,499**	**20.50**	**1,358**	**336**	**20.50**	**5,555**	**1,485**	**21.40**
-		**Minimum**	**5,641**	**0**	**0**	**736**	**0**	**0**	**3,261**	**0**	**0**

Table E-6 Target quantities and potential reduction by CRS model of Technical performance of Lam Sieo Yai basin (Cont'd)

DMU	Rice cropping system	Methods	Cost of fertilizer			Cost of pesticide			Cost of machinery		
			Target	Potential reduction	Difference (%)	Target	Potential reduction	Difference (%)	Target	Potential reduction	Difference (%)
21	wet season irrigated	dry seeding	8,003	5,372	40.17	1,589	1,067	40.17	3,832	2,491	39.40
22			10,055	3,320	24.82	1,997	659	24.82	4,814	1,509	23.86
23			10,020	3,355	25.08	1,990	666	25.08	4,797	1,525	24.12
24			8,592	4,783	35.76	1,706	950	35.76	4,114	2,209	34.94
25			9,714	3,661	27.38	1,929	727	27.38	4,651	1,672	26.45
26			10,011	3,364	25.15	1,988	668	25.15	4,793	1,530	24.19
27			8,736	4,639	34.68	1,735	921	34.68	4,183	2,140	33.85
28			10,722	2,653	19.84	1,893	413	17.91	5,477	1,195	17.91
29			10,446	2,929	21.90	2,075	591	22.16	5,002	1,312	20.78
30			10,030	3,345	25.01	1,992	664	25.01	4,802	1,521	24.05
31			10,238	3,137	23	1,808	499	22	5,230	1,442	22
32			9,776	3,599	26.91	1,942	724	27.16	4,681	1,633	25.86
33			9,402	3,973	29.71	1,867	789	29.71	4,501	1,821	28.81
34			10,229	3,146	23.52	2,031	634	23.79	4,897	1,416	22.43
35			10,771	2,604	19.47	1,887	420	18.20	5,524	1,229	18.20
36		transplanting	13,375	0	0	2,656	0	0	6,404	0	0
37			12,527	848	6	2,195	112	5	6,425	328	5
38			12,649	726	5.43	2,512	144	5.43	6,056	156	2.51
39		wet seeding	10,795	2,580	19.29	2,144	512	19.29	5,168	1,043	16.80
40			11,317	2,058	15.39	2,248	409	15.39	5,418	793	12.77
-		**Maximum**	**13,375**	**5,372**	**40.17**	**2,656**	**1,067**	**40.17**	**6,425**	**2,491**	**39.40**
-		**Median**	**10,142**	**3,233**	**24.17**	**1,989**	**647**	**24.30**	**4,856**	**1,476**	**23.15**
-		**Minimum**	**8,003**	**0**	**0**	**1,589**	**0**	**0**	**3,832**	**0**	**0**

Table E-6 Target quantities and potential reduction by CRS model of Technical performance of Lam Sieo Yai basin (Cont’d)

DMU	**Rice cropping system**	**Methods**	**Cost of fertilizer**			**Cost of pesticide**			**Cost of machinery**		
			Target	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**	**Target**	**Potential reduction**	**Difference (%)**
41	**dry season irrigated**	**dry seeding**	5,733	7,642	57.14	1,138	2,143	65.30	2,745	3,542	56.34
42			5,360	8,015	59.93	1,064	2,217	67.56	2,566	3,720	59.18
43			4,489	8,886	66.43	892	2,390	72.83	2,149	4,137	65.81
44			3,619	9,756	72.94	719	2,563	78.10	1,733	4,554	72.44
45			3,619	9,756	72.94	719	2,563	78.10	1,733	4,554	72.44
46			2,277	11,098	82.97	452	2,829	86.22	1,090	5,196	82.66
47			4,636	8,739	65.34	921	2,361	71.94	2,219	4,067	64.70
48			2,879	10,496	78.48	572	2,553	81.70	1,378	2,849	67.40
49			2,873	10,502	78.52	571	2,711	82.61	1,375	2,852	67.47
50			4,636	8,739	65.34	921	2,361	71.94	2,219	2,675	54.65
51			3,047	10,328	77.22	605	2,676	81.56	1,459	3,435	70.19
52			2,720	10,655	79.66	540	2,585	82.71	1,303	3,081	70.29
53			4,636	8,739	65.34	921	2,361	71.94	2,219	4,067	64.70
54		**wet seeding**	7,617	5,758	43.05	1,513	1,768	53.90	3,647	3,112	46.04
55			5,360	8,015	59.93	1,064	2,061	65.94	2,566	4,349	62.89
56			6,790	6,585	49.23	1,349	1,933	58.90	3,251	3,192	49.54
57			7,826	5,549	41.49	1,554	1,727	52.63	3,747	2,540	40.40
58		**transplanting**	8,794	4,581	34.25	1,747	1,378	44.11	4,211	2,076	33.03
59			8,749	4,626	34.59	1,738	1,387	44.40	4,189	2,098	33.37
60			8,705	4,670	34.91	1,729	1,396	44.68	4,168	2,275	35.31
-		**Maximum**	**8,794**	**11,098**	**82.97**	**1,747**	**2,829**	**86.22**	**4,211**	**5,196**	**82.66**
-		**Median**	**4,636**	**8,739**	**65.34**	**921**	**2,361**	**71.94**	**2,219**	**3,314**	**63.79**
-		**Minimum**	**2,277**	**4,581**	**34.25**	**452**	**1378.49**	**44.11**	**1,090**	**2,076**	**33.03**

Table E-7 Variables inputs and output for environmental efficiency assessment of Nam Mae Lao Basin

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**						**Variable output**
			GWP$_{100}$ kg CO_2-eq	**EP** kg PO_4-eq	**AP** kg SO_2-eq	**FAETP** kg 1,4-DB eq	**WDP** m^3 eq	**FEU** MJ eq	**Yield** kg/ha
1	**Rainfed**	**dry seeding**	6,778	188.16	94.78	254.53	0.00395	2,541	2,679
2			7,053	179.40	94.90	286.98	0.00395	2,537	3,095
3			7,031	219.69	96.25	265.00	0.00493	2,535	2,976
4			7,184	213.13	96.25	265.03	0.00320	2,777	3,274
5			6,778	188.16	94.78	254.53	0.00197	2,775	2,679
6			7,081	175.31	94.88	293.56	0.00320	2,777	3,274
7			7,031	219.69	96.25	265.00	0.00461	2,541	2,976
8			7,031	219.69	96.25	265.00	0.00395	2,554	2,976
9			6,863	226.13	96.19	265.22	0.00459	2,538	2,679
10			6,938	181.88	94.69	254.69	0.00247	2,776	3,005
11			7,056	140.45	93.74	254.40	0.00395	2,533	3,155
12			7,184	213.13	96.25	265.03	0.00461	2,541	3,274
13			6,938	144.06	93.75	166.25	0.00461	2,541	2,976
14			6,778	188.16	94.78	254.53	0.00459	2,538	2,679
15		**wet seeding**	7,964	176.24	100.07	484.40	30.00921	2,707	3,298
16		**transplanting**	8,136	159.40	95.71	471.20	30.00875	2,851	3,690
17			7,731	162.09	95.48	388.31	30.00938	3,285	3,571
18			7,912	191.81	96.87	478.56	30.00938	3,285	3,869
19			7,576	203.78	96.66	473.52	30.00938	3,285	3,274
20			7,609	167.85	95.68	473.52	30.00938	3,285	3,274
-		**Maximum**	**8,136**	**226.13**	**100.07**	**484.40**	**30.00938**	**3,285**	**3,869**
-		**Median**	**7,054**	**188.16**	**95.70**	**265.03**	**0.00460**	**2,630**	**3,125**
-		**Minimum**	**6,778**	**140.45**	**93.74**	**166.25**	**0.00197**	**2,533**	**2,679**

Table E-7 Variables inputs and output for environmental efficiency assessment of Nam Mae Lao Basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**						**Variable output**
			GWP$_{100}$	**EP**	**AP**	**FAETP**	**WDP**	**FEU**	**Yield**
			kg CO_2-eq	kg PO_4-eq	kg SO_2-eq	kg 1,4-DB eq	m^3 eq	MJ eq	kg/ha
21	**wet season irrigated**	**dry seeding**	9,866	175.31	94.88	259.53	0.00179	2,795	3,274
22			9,866	175.31	94.88	259.53	0.00171	2,795	3,274
23		**wet seeding**	11,131	201.50	101.56	491.56	30.00472	2,639	3,869
24			10,875	170.25	100.13	483.75	30.00987	2,694	3,571
25			10,375	183.13	100.00	478.13	30.00921	2,707	2,976
26			10,838	170.25	100.13	480.00	30.00434	2,605	3,571
27			10,723	174.21	100.11	448.88	30.00395	2,440	3,393
28			10,656	176.69	100.03	484.69	30.00411	2,416	3,274
29			10,588	138.88	99.00	477.81	30.00625	2,536	3,274
30			10,588	138.88	99.00	477.81	30.00625	2,536	3,274
31			10,730	134.13	98.96	391.50	30.00921	2,707	3,452
32			10,875	170.25	100.13	483.75	30.00395	2,447	3,571
33			10,656	176.69	100.03	484.69	30.00625	2,536	3,274
34			10,656	176.69	100.03	484.69	30.00625	2,536	3,274
35			10,872	169.88	100.04	483.20	30.00921	2,707	3,452
36			11,223	199.33	101.34	489.94	30.00402	2,580	3,988
37			11,091	164.13	100.34	483.44	30.00987	2,694	3,869
38		**transplanting**	10,709	157.89	96.53	476.80	30.00728	2,673	3,869
39			10,407	130.71	96.01	469.56	30.00875	2,639	3,452
40			10,513	128.33	95.70	471.25	30.00875	2,639	3,571
-		**Maximum**	**11,223**	**201.50**	**101.56**	**491.56**	**30.0099**	**2,795**	**3,988**
-		**Median**	**10,682**	**170.25**	**100.03**	**479.06**	**30.0063**	**2,639**	**3,452**
-		**Minimum**	**9,866**	**128.33**	**94.88**	**259.53**	**0.0017**	**2,416**	**2,976**

Table E-7 Variables inputs and output for environmental efficiency assessment of Nam Mae Lao Basin (Cont’d)

DMU	Rice cropping system	Methods	Variable inputs (Unit/ha)						Variable output
			GWP$_{100}$ kg CO_2-eq	EP kg PO_4-eq	AP kg SO_2-eq	FAETP kg 1,4-DB eq	WDP m^3 eq	FEU MJ eq	Yield kg/ha
41	**dry season irrigated**	**dry seeding**	6,719	183.44	101.88	556.25	39.7018	3,118	2,976
42			6,760	181.03	101.73	559.00	39.7017	3,062	3,095
43			6,841	214.16	102.44	556.88	39.7019	3,380	3,274
44			6,841	177.03	101.75	556.88	39.7066	3,722	3,274
45			6,656	183.13	101.25	550.00	39.7066	3,785	3,274
46		**wet seeding**	7,688	172.13	106.88	776.25	69.7043	2,961	3,571
47			7,631	178.41	106.91	783.75	69.7039	2,630	3,274
48			7,631	178.41	106.91	783.75	69.7041	2,583	3,274
49			7,469	147.19	105.63	778.13	69.7063	2,827	2,976
50			7,597	140.59	105.88	776.88	69.7063	2,827	3,274
51			7,649	137.03	105.85	688.75	69.7092	3,151	3,452
52			7,763	172.13	106.88	783.75	69.7039	2,645	3,571
53			7,631	178.41	106.91	783.75	69.7063	2,827	3,274
54			7,500	184.69	106.88	781.25	69.7063	2,827	2,976
55			7,763	172.13	106.88	783.75	69.7092	3,151	3,571
56			7,666	2,162.19	1,082.81	787.19	69.7040	2,909	3,274
57			7,763	172.13	106.88	783.75	69.7099	3,138	3,571
58		**transplanting**	7,403	169.30	103.16	757.41	67.7691	3,118	3,393
59			7,344	135.91	102.35	754.30	67.9527	3,076	3,274
60			7,404	133.62	102.28	754.18	67.9527	3,076	3,393
-		**Maximum**	**7,763**	**2,162**	**1,083**	**787.19**	**69.7099**	**3,785**	**3,571**
-		**Median**	**7,548**	**174.58**	**105.86**	**776.56**	**69.704**	**3,069**	**3,274**
-		**Minimum**	**6,656**	**133.62**	**101.25**	**550.00**	**39.7017**	**2,583**	**2,976**

Table E-8 EE analysis, as per rice cropping systems of Nam Mae Lao basin

DMU	**Rice cropping system**	**Methods**	**Environmental efficiencies score**		
			CRS	**VRS**	**SC**
1	**Rainfed**	**dry seeding**	0.866178	1	0.866178
2			0.977238	0.998958	0.978257
3			0.926528	0.999669	0.926835
4			1	1	1
5			0.994628	1	0.994628
6			1	1	1
7			0.926528	0.997286	0.92905
8			0.934832	0.993879	0.940589
9			0.851783	0.999444	0.852256
10			1	1	1
11			1	1	1
12			1	1	1
13			1	1	1
14			0.866178	1	0.866178
15		**wet seeding**	0.927941	0.948577	0.978246
16		**transplanting**	1	1	1
17			1	1	1
18			1	1	1
19			0.883424	0.974322	0.906706
20			0.909896	0.984298	0.924411
-		**Maximum**	**1**	**1**	**1**
-		**Median**	**0.985933**	**1**	**0.986442**
-		**Minimum**	**0.851783**	**0.948577**	**0.852256**
21	**wet season irrigated**	**dry seeding**	0.904157	1	0.904157
22			0.934977	1	0.934977
23		**wet seeding**	0.97576	0.980106	0.995565
24			0.975834	0.960357	1
25			1	0.937428	1
26			0.98304	0.974258	1
27			0.955656	1	0.955656
28			0.966606	1	0.966606
29			0.876769	1	0.876769
30			0.986414	1	0.986414
31			1	1	1
32			1	1	1
33			0.909519	0.973934	0.933861
34			0.836836	0.973934	0.859233
35			0.964592	0.952517	1
36			0.898766	1	0.898766
37			0.965219	0.987213	0.977721
38		**transplanting**	0.950472	1	0.950472
39			0.968021	0.994459	0.973415
40			0.904157	1	0.904157
-		**Maximum**	**1**	**1**	**1**
-		**Median**	**0.965912**	**1**	**0.975568**
-		**Minimum**	**0.836836**	**0.937428**	**0.859233**

Table E-8 EE analysis, as per rice cropping systems of Nam Mae Lao basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Environmental efficiencies score**		
			CRS	**VRS**	**SC**
41	**dry season irrigated**	**dry seeding**	1	1	1
42			1	1	1
43			0.966661	0.998374	0.968234
44			0.906	0.990929	0.914294
45			0.760102	1	0.760102
46		**wet seeding**	0.925465	0.990552	0.934293
47			0.921609	0.970252	0.949865
48			0.889441	0.982633	0.905161
49			0.916434	0.952774	0.961859
50			0.916434	1	0.916434
51			1	1	1
52			0.970292	1	0.970292
53			0.858163	0.939722	0.91321
54			0.858163	0.924344	0.928403
55			0.874214	0.97339	0.898113
56			1	0.92813	1
57			0.986842	0.973543	1
58		**transplanting**	1	0.984604	1
59			0.964168	0.996042	0.967999
60			1	1	1
-		**Maximum**	**1**	**1**	**1**
-		**Median**	**0.944817**	**0.99074**	**0.96492907**
-		**Minimum**	**0.760102**	**0.924344**	**0.760102**

Table E-9 Target quantities and potential reduction by CRS model of Technical performance of Nam Mae Lao basin

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**											
			GWP100 (kg CO2-eq)		**EP (kg PO4-eq)**		**AP (kg SO2-eq)**		**FAETP (kg 1,4-DB eq)**		**WDP (m^3 eq)**		**FEU (MJ eq)**	
			Target	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**
1	**Rainfed**	**dry seeding**	5871.06	-907.06	162.98	-25.18	78.69	-16.09	220.47	-34.06	0.0034	-0.0005	2150.69	-390.34
2			6891.97	-160.53	175.32	-4.08	90.96	-3.94	255.66	-31.32	0.0039	-0.0001	2479.06	-57.74
3			6514.65	-516.60	187.66	-32.02	87.28	-8.97	245.53	-19.47	0.0040	-0.0010	2348.46	-186.23
4			7184.38	0.00	213.13	0.00	96.25	0.00	265.03	0.00	0.0032	0.0000	2776.74	0.00
5			6741.71	-36.41	156.61	-31.55	82.40	-12.38	222.70	-31.83	0.0020	0.0000	2419.01	-355.55
6			7081.25	0.00	175.31	0.00	94.88	0.00	293.56	0.00	0.0032	0.0000	2776.74	0.00
7			6514.65	-516.60	187.66	-32.02	87.28	-8.97	245.53	-19.47	0.0040	-0.0006	2347.97	-193.06
8			6573.04	-458.21	183.62	-36.06	87.13	-9.12	247.73	-17.27	0.0037	-0.0003	2387.30	-166.42
9			5845.36	-1017.14	162.36	-63.76	78.31	-17.87	225.91	-39.31	0.0033	-0.0013	2153.91	-384.27
10			6937.50	0.00	181.88	0.00	94.69	0.00	254.69	0.00	0.0025	0.0000	2775.83	0.00
11			7055.63	0.00	140.45	0.00	93.74	0.00	254.40	0.00	0.0039	0.0000	2533.41	0.00
12			7184.38	0.00	213.13	0.00	96.25	0.00	265.03	0.00	0.0046	0.0000	2541.03	0.00
13			6937.50	0.00	144.06	0.00	93.75	0.00	166.25	0.00	0.0046	0.0000	2541.03	0.00
14			5871.06	-907.06	162.98	-25.18	78.69	-16.09	220.47	-34.06	0.0034	-0.0011	2146.58	-391.60
15		**wet seeding**	7410.79	-552.96	144.00	-32.24	85.40	-14.66	419.92	-64.48	26.6733	-3.3359	2518.68	-187.93
16		**transplanting**	8135.56	0.00	159.40	0.00	95.71	0.00	471.20	0.00	30.0088	0.0000	2851.33	0.00
17			7730.63	0.00	162.09	0.00	95.48	0.00	388.31	0.00	30.0094	0.0000	3284.70	0.00
18			7911.72	0.00	191.81	0.00	96.87	0.00	478.56	0.00	30.0094	0.0000	3284.70	0.00
19			6691.56	-884.69	163.92	-39.85	83.47	-13.20	416.21	-57.30	26.5051	-3.5043	2857.55	-427.15
20			6930.10	-678.80	152.88	-14.97	83.29	-12.39	410.83	-62.69	25.9463	-4.0631	2666.67	-618.03
-		**Maximum**	**8135.56**	**0.00**	**213.13**	**0.00**	**96.87**	**0.00**	**478.56**	**0.00**	**30.0094**	**0.0000**	**3284.70**	**0.00**
-		**Median**	**6933.80**	**-98.47**	**163.45**	**-9.53**	**89.12**	**-6.45**	**255.17**	**-18.37**	**0.0040**	**-0.0001**	**2537.22**	**-112.08**
-		**Minimum**	**5845.36**	**-1017.14**	**140.45**	**-63.76**	**78.31**	**-17.87**	**166.25**	**-64.48**	**0.0020**	**-4.0631**	**2146.58**	**-618.03**
21	**wet season irrigated**	**dry seeding**	6074.80	-643.95	153.60	-29.83	80.12	-21.75	410.32	-145.93	0.0018	0.0000	2819.27	-298.85
22			6320.44	-439.56	158.31	-22.72	82.00	-19.73	416.70	-142.30	0.0017	0.0000	2862.48	-199.07
23		**wet seeding**	6674.81	-165.82	173.03	-41.13	91.90	-10.53	479.68	-77.19	29.0044	-1.0003	3297.70	-81.92
24			6675.32	-165.31	172.75	-4.28	91.65	-10.10	477.75	-79.13	27.1807	-2.8291	3284.28	-437.61
25			6656.25	0.00	183.13	0.00	101.25	0.00	550.00	0.00	21.9932	-8.0160	3785.36	0.00
26			7557.12	-130.38	169.21	-2.92	91.23	-15.65	443.11	-333.14	27.3997	-2.6046	2910.39	-50.21
27			7292.85	-338.40	142.25	-36.16	84.84	-22.07	417.40	-366.35	25.3592	-4.6447	2513.78	-116.64
28			7376.41	-254.84	143.18	-35.23	84.77	-22.14	416.74	-367.01	24.7941	-5.2100	2496.55	-86.25
29			6548.37	-920.38	129.05	-18.14	77.12	-28.51	379.69	-398.44	26.2302	-3.7761	2305.47	-522.01
30			7493.67	-103.21	138.68	-1.91	85.23	-20.65	419.60	-357.28	26.2302	-3.7761	2516.84	-310.64
31			7648.75	0.00	137.03	0.00	105.85	0.00	688.75	0.00	30.0092	0.0000	3151.08	0.00
32			7762.50	0.00	172.13	0.00	106.88	0.00	783.75	0.00	27.2064	-2.7975	2644.53	0.00
33			6940.77	-690.48	159.66	-18.75	91.32	-15.58	588.26	-195.49	24.9393	-5.0669	2571.65	-255.83
34			6276.27	-1223.73	145.50	-39.18	81.75	-25.13	509.83	-271.42	24.9393	-5.0669	2366.14	-461.34
35			7487.64	-274.86	166.03	-6.09	93.82	-13.05	520.19	-263.56	26.0598	-3.9494	3039.51	-111.57
36			6889.60	-776.02	160.21	-2001.98	89.38	-993.43	550.17	-237.02	30.0040	0.0000	2614.81	-294.52

Table E-9 Target quantities and potential reduction by CRS model of Technical performance of Nam Mae Lao basin (Cont'd)

DMU	Rice cropping system	Methods	Variable inputs (Unit/ha)											
			GWP100 (kg CO2-eq)		EP (kg PO4-eq)		AP (kg SO2-eq)		FAETP (kg 1,4-DB eq)		WDP (m^3 eq)		FEU (MJ eq)	
			Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction
37	**wet season irrigated**		7492.51	-269.99	166.14	-5.99	93.57	-13.31	514.18	-269.57	29.6150	-0.3949	3029.23	-109.16
38		**transplanting**	7036.14	-366.65	160.92	-8.39	88.60	-14.56	490.12	-267.30	30.0073	0.0000	2921.66	-195.89
39			7108.80	-234.84	131.56	-4.35	97.37	-4.97	702.26	-52.04	28.7721	-1.2366	2953.38	-122.84
40			7404.06	0.00	133.62	0.00	102.28	0.00	754.18	0.00	30.0088	0.0000	3076.22	0.00
-		**Maximum**	**7762.50**	**0.00**	**183.13**	**0.00**	**106.88**	**0.00**	**783.75**	**0.00**	**30.0092**	**0.0000**	**3785.36**	**0.00**
-		**Median**	**7072.47**	**-262.41**	**158.98**	**-7.24**	**91.27**	**-15.07**	**499.97**	**-216.26**	**26.7055**	**-2.7011**	**2886.44**	**-119.74**
-		**Minimum**	**6074.80**	**-1223.73**	**129.05**	**-2001.98**	**77.12**	**-993.43**	**379.69**	**-398.44**	**0.0017**	**-8.0160**	**2305.47**	**-522.01**
41	**dry season irrigated**	**dry seeding**	9865.63	0.00	175.31	0.00	94.88	0.00	259.53	0.00	27.2472	-12.4546	2794.87	0.00
42			9865.63	0.00	175.31	0.00	94.88	0.00	259.53	0.00	27.3474	-12.3543	2794.87	0.00
43			10760.14	-371.11	189.36	-12.14	98.18	-3.39	474.24	-17.32	32.7678	-6.9340	2550.91	-87.98
44			9852.75	-1022.25	154.25	-16.00	89.81	-10.31	438.28	-45.47	32.5770	-7.1296	2440.69	-253.23
45			7886.06	-2488.94	139.19	-43.93	76.01	-23.99	363.42	-114.70	39.7066	0.0000	2057.30	-649.31
46		**wet seeding**	9944.39	-893.11	157.56	-12.69	89.70	-10.43	439.63	-40.37	27.4275	-42.2768	2410.86	-194.16
47			9477.15	-1245.97	160.55	-13.66	86.08	-14.02	413.69	-35.19	26.5450	-43.1589	2248.66	-191.27
48			9179.86	-1476.39	157.15	-19.53	82.86	-17.17	402.46	-82.23	26.4617	-43.2424	2148.99	-267.12
49			9289.19	-1298.31	127.27	-11.61	84.08	-14.92	414.76	-63.05	24.1711	-45.5352	2324.33	-211.95
50			9289.19	-1298.31	127.27	-11.61	84.08	-14.92	414.76	-63.05	26.7221	-42.9841	2324.33	-211.95
51			10730.00	0.00	134.13	0.00	98.96	0.00	391.50	0.00	69.7092	0.0000	2706.61	0.00
52			9982.88	-892.12	165.19	-5.06	90.08	-10.04	439.31	-44.44	69.7039	0.0000	2374.29	-72.69
53			9145.02	-1511.23	151.63	-25.06	82.60	-17.43	402.75	-81.94	47.9074	-21.7988	2176.59	-359.69
54			9145.02	-1511.23	151.63	-25.06	82.60	-17.43	402.75	-81.94	40.4873	-29.2190	2176.59	-359.69
55			9504.45	-1367.55	148.51	-21.37	86.93	-13.11	422.42	-60.78	37.4044	-32.3048	2366.15	-340.45
56			11222.50	0.00	199.33	0.00	101.34	0.00	489.94	0.00	43.2290	-26.4751	2580.09	0.00
57			10708.33	-382.29	161.97	-2.16	96.91	-3.43	475.03	-8.41	36.6464	-33.0634	2658.47	-35.45
58		**transplanting**	10708.54	0.00	157.89	0.00	96.53	0.00	476.80	0.00	35.0853	-32.6837	2673.08	0.00
59			10034.46	-372.92	126.02	-4.68	92.02	-4.00	452.73	-16.83	62.3999	-5.5528	2544.83	-94.58
60			10512.50	0.00	128.33	0.00	95.70	0.00	471.25	0.00	67.9527	0.0000	2639.41	0.00
-		**Maximum**	**11222.50**	**0.00**	**199.33**	**0.00**	**101.34**	**0.00**	**489.94**	**0.00**	**69.7092**	**0.0000**	**2794.87**	**0.00**
-		**Median**	**9865.63**	**-892.61**	**155.70**	**-11.61**	**89.95**	**-10.18**	**418.59**	**-37.78**	**35.8659**	**-24.1369**	**2425.77**	**-142.92**
-		**Minimum**	**7886.06**	**-2488.94**	**126.02**	**-43.93**			**259.53**	**-114.70**	**24.1711**	**-45.5352**	**2057.30**	**-649.31**

Table E-10 Variables inputs and output for environmental efficiency assessment of Lam Sieo Yai Basin

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**						**Variable output**
			GWP$_{100}$	**EP**	**AP**	**FAETP**	**WDP**	**FEU**	**Yield**
			kg CO_2-eq	kg PO_4-eq	kg SO_2-eq	kg 1,4-DB eq	m^3 eq	MJ eq	kg/ha
1	**Rainfed**	**dry seeding**	8,052	215.11	120.86	760.44	0.105	2,615	2,219
2			7,001	192.11	109.11	686.44	0.105	2,609	2,500
3			7,643	202.33	114.33	719.33	0.105	2,612	2,375
4			7,055	177.57	104.12	653.26	0.105	2,603	2,500
5			8,134	217.67	122.17	818.00	0.105	2,616	2,188
6			7,002	192.11	100.26	650.13	0.105	2,595	2,500
7			7,971	178.96	119.56	752.22	0.105	2,614	2,250
8			7,646	185.70	101.26	719.33	0.105	2,596	2,375
9			8,625	233.00	130.00	650.13	0.105	2,595	2,000
10			6,896	170.57	98.57	640.24	0.105	2,596	2,500
11			7,023	178.60	110.26	700.46	0.105	2,608	2,375
12			7,316	178.60	104.12	653.00	0.105	2,603	2,500
13			7,480	197.22	111.72	702.89	0.105	2,610	2,438
14			8,134	217.67	102.88	700.26	0.105	2,620	2,188
15			7,054	170.60	109.11	625.15	0.105	2,609	2,500
16		**transplanting**	5,680	141.00	83.00	522.00	1,260	2,595	3,125
17			6,498	160.58	96.06	604.22	1,260	2,602	2,813
18			6,112	138.53	84.50	522.00	1,260	2,595	3,125
19		**wet seeding**	6,498	166.56	96.13	600.13	0.087	2,602	2,813
20			6,498	160.90	96.26	598.56	0.087	2,602	2,813
-		**Maximum**	**8,625**	**233.00**	**130.00**	**818.00**	**1,260**	**2,620**	**3,125**
-		**Median**	**7,054**	**178**	**104.12**	**653.13**	**0.105**	**2,603**	**2,500**
-		**Minimum**	**5,680**	**138.53**	**83.00**	**522.00**	**0.087**	**2,595**	**2,000**

Table E-10 Variables inputs and output for environmental efficiency assessment of Lam Sieo Yai Basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**						**Variable output**
			GWP$_{100}$	**EP**	**AP**	**FAETP**	**WDP**	**FEU**	**Yield**
			kg CO_2-eq	kg PO_4-eq	kg SO_2-eq	kg 1,4-DB eq	m^3 eq	MJ eq	kg/ha
21	**wet season irrigated**	**dry seeding**	12,550	200.85	103.38	769.85	311.22	2,943	2,938
22			13,795	227.92	115.69	860.92	311.22	2,957	2,688
23			13,172	214.38	109.54	780.26	311.22	2,950	2,813
24			12,757	200.13	105.69	815.38	311.22	2,953	2,813
25			15,040	255.00	128.00	952.00	311.22	2,972	2,438
26			12,659	208.13	100.26	790.37	311.22	2,950	2,813
27			14,106	234.69	106.26	952.00	311.22	2,961	2,625
28			15,040	255.00	127.57	790.25	311.22	2,972	2,438
29			12,790	210.48	111.15	883.69	311.22	2,961	2,625
30			12,784	206.33	100.26	784.26	311.22	2,961	2,625
31			14,729	248.23	124.92	929.23	311.22	2,968	2,500
32			12,369	220.15	120.26	850.13	311.22	2,968	2,500
33			12,785	198.57	106.59	775.37	311.22	2,950	2,813
34			13,483	221.15	112.62	838.15	311.22	2,954	2,750
35			12,786	208.56	124.92	920.13	311.22	2,968	2,500
36		**transplanting**	10,993	167.00	88.00	656.00	1,260	2,925	3,250
37			11,304	173.77	91.08	678.77	1,260	2,928	3,188
38			11,616	180.54	94.15	701.54	1,260	2,932	3,125
39		**wet seeding**	12,116	194.08	100.31	745.26	310.8	2,939	3,000
40			12,238	194.08	98.24	747.08	310.8	2,939	3,000
-		**Maximum**	**15,040**	**255.00**	**128.00**	**952.00**	1,260	**2,972**	**3,250**
-		**Median**	**12,784**	**208.34**	**106.42**	**790.31**	311.22	**2,953**	**2,781**
-		**Minimum**	**10,993**	**167.00**	**88.00**	**656.00**	310.8	**2,925**	**2,438**

Table E-10 Variables inputs and output for environmental efficiency assessment of Lam Sieo Yai Basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**						**Variable output**
			GWP$_{100}$ kg CO_2-eq	**EP** kg PO_4-eq	**AP** kg SO_2-eq	**FAETP** kg 1,4-DB eq	**WDP** m^3 eq	**FEU** MJ eq	**Yield** kg/ha
41	**dry season irrigated**	**dry seeding**	12,652	231.68	112.63	852.84	2,555	2,979	2,438
42			13,918	261.16	125.68	1,075.00	2,555	3,060	2,188
43			12,969	239.05	115.89	877.53	2,555	2,999	2,375
44			12,336	224.32	109.37	828.16	2,555	2,958	2,500
45			15,489	298.00	142.00	801.59	2,555	3,161	1,875
46			12,001	210.36	109.37	800.13	2,555	2,982	2,500
47			12,898	260.55	110.37	951.58	2,555	3,060	2,188
48			15,500	295.00	135.00	803.37	2,555	3,161	1,875
49			12,146	223.56	107.59	924.56	2,555	3,060	2,188
50			12,059	199.46	105.27	900.26	2,555	3,060	2,188
51			12,148	210.01	107.51	900.24	2,555	3,060	2,188
52			11,001	225.15	106.24	911.18	2,555	3,060	2,188
53			11,599	210.57	107.46	811.46	2,555	3,060	2,188
54		**wet seeding**	12,137	224.32	106.58	801.26	2,555	2,776	2,500
55			12,336	205.59	100.24	800.37	2,555	2,958	2,500
56			10,754	187.47	93.05	704.74	3,815	2,857	2,813
57			11,387	198.66	99.58	754.11	3,815	2,897	2,688
58		**transplanting**	9,488	158.00	80.00	606.00	3,815	2,776	3,063
59			9,963	169.05	84.89	643.03	2,555	2,806	2,969
60			10,121	172.74	86.53	655.37	2,555	2,816	2,938
-		**Maximum**	**15,500**	**298**	**142**	**1,075.00**	3,815	**3,161**	**3,063**
-		**Median**	**12,141**	**217.06**	**107.48**	**807.41**	2,555	**2,991**	**2,406**
-		**Minimum**	**9,488**	**158.00**	**80.00**	**606.00**	2,555	**2,776**	**1,875**

Table E-11 EE analysis, as per rice cropping systems of Lam Sieo Yai basin

DMU	**Rice cropping system**	**Methods**	**Environmental efficiencies score**		
			CRS	**VRS**	**SC**
1	**Rainfed**	**dry seeding**	0.7123	1.0000	0.7123
2			0.8025	1.0000	0.8025
3			0.7624	1.0000	0.7624
4			0.8025	1.0000	0.8025
5			0.7022	1.0000	0.7022
6			0.8025	1.0000	0.8025
7			0.7223	1.0000	0.7223
8			0.7624	1.0000	0.7624
9			0.6420	1.0000	0.6420
10			0.8025	1.0000	0.8025
11			0.7624	1.0000	0.7624
12			0.8025	1.0000	0.8025
13			0.7825	1.0000	0.7825
14			0.7022	1.0000	0.7022
15			0.8025	1.0000	0.8025
16		**transplanting**	1.0000	1.0000	1.0000
17			0.9000	0.9984	0.9014
18			1.0000	1.0000	1.0000
19		**wet seeding**	0.9014	1.0000	0.9014
20			0.9014	1.0000	0.9014
-		**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.8025**	**1.0000**	**0.8025**
-		**Minimum**	**0.6420**	**0.9984**	**0.6420**
21	**wet season irrigated**	**dry seeding**	0.8435	0.8965	0.9409
22			0.7717	0.8954	0.8619
23			0.8076	0.8960	0.9014
24			0.8076	0.8960	0.9014
25			0.7000	0.8945	0.7825
26			0.8076	0.8961	0.9013
27			0.7538	0.8952	0.8421
28			0.7000	0.8945	0.7825
29			0.7538	0.8951	0.8421
30			0.7538	0.8961	0.8412
31			0.7179	0.8945	0.8025
32			0.7179	0.8945	0.8025
33			0.8076	0.8960	0.9014
34			0.7897	0.8957	0.8817
35			0.7179	0.8945	0.8025
36		**transplanting**	0.9763	1.0000	0.9763
37			0.9280	0.9470	0.9800
38			0.8939	0.8939	1.0000
39		**wet seeding**	0.8604	0.8957	0.9606
40			0.8604	0.8957	0.9606
-		**Maximum**	**0.9763**	**1.0000**	**1.0000**
-		**Median**	**0.7987**	**0.8957**	**0.8915**
-		**Minimum**	**0.7000**	**0.8939**	**0.7825**

Table E-11 EE analysis, as per rice cropping systems of Lam Sieo Yai basin (Cont’d)

DMU	**Rice cropping system**	**Methods**	**Environmental efficiencies score**		
			CRS	**VRS**	**SC**
41	**dry season irrigated**	**dry seeding**	0.6796	0.8713	0.7800
42			0.6083	0.8662	0.7022
43			0.6604	0.8662	0.7624
44			0.7018	0.8773	0.8000
45			0.5214	0.8662	0.6019
46			0.6962	0.8702	0.8000
47			0.6083	0.8667	0.7018
48			0.5214	0.8662	0.6019
49			0.6083	0.8671	0.7015
50			0.6083	0.8675	0.7012
51			0.6083	0.8671	0.7015
52			0.6083	0.8673	0.7013
53			0.6083	0.8671	0.7015
54		**wet seeding**	0.7480	0.9350	0.8000
55			0.7018	0.8773	0.8000
56			0.8176	0.9085	0.9000
57			0.7703	0.8957	0.8600
58		**transplanting**	1.0000	1.0000	1.0000
59			0.9208	0.9590	0.9602
60			0.8961	0.9460	0.9472
-		**Maximum**	**1.0000**	**1.0000**	**1.0000**
-		**Median**	**0.6700**	**0.8688**	**0.7712**
-		**Minimum**	**0.5214**	**0.8662**	**0.6019**

Table E-12 Target quantities and potential reduction by CRS model of Technical performance of Lam Sieo Yai basin

DMU	Rice cropping system	Methods	Variable inputs (Unit/ha)											
			GWP100 (kg CO2-eq)		EP (kg PO4-eq)		AP (kg SO2-eq)		FAETP (kg 1,4-DB eq)		WDP (m^3 eq)		FEU (MJ eq)	
			Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction	Target	Potential reduction
1	**Rainfed**	**dry seeding**	4,033	4,020	100.11	115.00	58.93	61.93	370.62	389.82	0.030	0.075	1,843	772.21
2			4,544	2,457	112.80	79.31	66.40	42.71	417.60	268.84	0.021	0.084	2,076	532.56
3			4,317	3,327	107.16	95.17	63.08	51.25	396.72	322.61	0.025	0.080	1,972	639.07
4			4,544	2,511	112.80	64.77	66.40	37.72	417.60	235.66	0.021	0.084	2,076	526.41
5			3,976	4,158	98.70	118.97	58.10	64.07	365.40	452.60	0.031	0.074	1,817	798.84
6			4,544	2,458	112.80	79.31	66.40	33.86	417.60	232.53	0.021	0.084	2,076	519.06
7			4,400	3,570	99.74	79.22	60.84	58.72	375.84	376.38	0.029	0.076	1,869	745.58
8			4,317	3,329	107.16	78.54	63.08	38.18	396.72	322.61	0.025	0.080	1,972	623.77
9			3,635	4,990	90.24	142.76	53.12	76.88	334.08	316.05	0.038	0.067	1,661	934.31
10			4,544	2,352	112.80	57.77	66.40	32.17	417.60	222.64	0.021	0.084	2,076	519.51
11			4,317	2,707	107.16	71.44	63.08	47.18	396.72	303.74	0.025	0.080	1,972	635.92
12			4,544	2,772	112.80	65.80	66.40	37.72	417.60	235.40	0.021	0.084	2,076	526.56
13			4,430	3,049	109.98	87.24	64.74	46.98	407.16	295.73	0.023	0.082	2,024	585.82
14			3,976	4,158	98.70	118.97	58.10	44.78	365.40	334.86	0.031	0.074	1,817	802.89
15			4,544	2,510	112.80	57.80	66.40	42.71	417.60	207.55	0.021	0.084	2,076	532.56
16		**transplanting**	5,680	0	141.00	0.00	83.00	0.00	522.00	0.00	0.000	1260.000	2,595	0.00
17			5,112	1,386	126.90	33.68	74.70	21.36	469.80	134.42	126.000	1134.000	2,336	266.28
18			6,112	0	138.53	0.00	84.50	0.00	522.00	0.00	0.000	1260.000	2,595	0.00
19		**wet seeding**	5,112	1,386	126.90	39.66	74.70	21.43	469.80	130.33	0.009	0.079	2,336	265.98
20			5,112	1,386	126.90	34.00	74.70	21.56	469.80	128.76	0.009	0.079	2,336	266.28
-		**Maximum**	**6,112**	**4,990**	**141.00**	**142.76**	**84.50**	**76.88**	**522.00**	**452.60**	**0.000**	**1260.000**	**2,595**	**934.31**
-		**Median**	**4,544**	**2,609**	**112.80**	**74.99**	**66.40**	**40.44**	**417.60**	**252.25**	**0.021**	**0.084**	**2,076**	**532.56**
-		**Minimum**	**3,635**	**0**	**90.24**	**0.00**	**53.12**	**0.00**	**334.08**	**0.00**	**0.031**	**0.056**	**1,661**	**0.00**
21	**wet season irrigated**	**dry seeding**	5,339	7,210	132.54	68.31	78.02	25.36	490.68	279.17	48.694	262.526	2,440	503.12
22			4,885	8,910	121.26	106.66	71.38	44.31	448.92	412.00	71.037	240.183	2,232	725.14
23			5,112	8,060	126.90	87.48	74.70	34.84	469.80	310.46	59.865	251.355	2,336	614.13
24			5,112	7,645	126.90	73.23	74.70	30.99	469.80	345.58	59.865	251.355	2,336	616.83
25			4,430	10,610	109.98	145.02	64.74	63.26	407.16	544.84	93.379	217.841	2,024	947.17
26			5,112	7,547	126.90	81.23	74.70	25.56	469.80	320.57	59.865	251.355	2,336	614.13
27			4,771	9,335	118.44	116.25	69.72	36.54	438.48	513.52	76.622	234.598	2,180	780.65
28			4,430	10,610	109.98	145.02	64.74	62.83	407.16	383.09	93.379	217.841	2,024	947.17
29			5,134	7,656	116.36	94.11	70.98	40.17	438.48	445.21	76.622	234.598	2,180	780.65
30			4,771	8,013	118.44	87.89	69.72	30.54	438.48	345.78	76.622	234.598	2,180	780.65
31			4,544	10,185	112.80	135.43	66.40	58.52	417.60	511.63	87.794	223.426	2,076	891.66
32			4,544	7,825	112.80	107.35	66.40	53.86	417.60	432.53	87.794	223.426	2,076	891.66
33			5,112	7,673	126.90	71.67	74.70	31.89	469.80	305.57	59.865	251.355	2,336	614.13
34			5,378	8,105	121.90	99.25	74.36	38.26	459.36	378.79	65.451	245.769	2,284	669.64
35			4,544	8,242	112.80	95.76	66.40	58.52	417.60	502.53	87.794	223.426	2,076	891.66

Table E-12 Target quantities and potential reduction by CRS model of Technical performance of Lam Sieo Yai basin (Cont'd)

DMU	**Rice cropping system**	**Methods**	**Variable inputs (Unit/ha)**											
			GWP100 (kg CO2-eq)		**EP (kg PO4-eq)**		**AP (kg SO2-eq)**		**FAETP (kg 1,4-DB eq)**		**WDP (m^3 eq)**		**FEU (MJ eq)**	
			Target	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**	**Target**	**Potential reduction**
36	**wet season irrigated**	**transplanting**	7,103	3,890	152.68	14.32	85.91	2.09	571.67	84.33	29.904	1230.096	2,770	154.79
37			6,209	5,096	145.92	27.85	84.52	6.56	542.43	136.33	90.737	1169.263	2,672	256.52
38			5,680	5,936	141.00	39.54	83.00	11.15	522.00	179.54	133.628	1126.372	2,595	336.60
39		**wet seeding**	5,453	6,663	135.36	58.72	79.68	20.63	501.12	244.14	43.393	267.407	2,491	447.61
40			5,453	6,785	135.36	58.72	79.68	18.56	501.12	245.96	43.393	267.407	2,491	447.61
-		**Maximum**	**7,103**	**10,610**	**152.68**	**145.02**	**85.91**	**63.26**	**571.67**	**544.84**	**29.904**	**1230.096**	**2,770**	**947.17**
-		**Median**	**5,112**	**7,749**	**124.40**	**87.68**	**74.53**	**33.36**	**464.58**	**345.68**	**62.658**	**248.562**	**2,310**	**643.23**
-		**Minimum**	**4,430**	**3,890**	**109.98**	**14.32**	**64.74**	**2.09**	**407.16**	**84.33**	**93.253**	**217.547**	**2,024**	**154.79**
41	**dry season irrigated**	**dry seeding**	4,430	8,222	109.98	121.70	64.74	47.89	407.16	445.68	823.388	1731.892	2,024	954.32
42			4,278	9,640	96.97	164.19	59.15	66.53	365.40	709.60	1001.018	1554.262	1,817	1,243.16
43			4,645	8,324	105.28	133.77	64.22	51.67	396.72	480.81	867.795	1687.485	1,972	1,026.53
44			4,889	7,447	110.82	113.49	67.60	41.77	417.60	410.56	778.980	1776.300	2,076	882.11
45			3,667	11,822	83.12	214.88	50.70	91.30	313.20	488.39	1223.055	1332.225	1,557	1,604.22
46			4,544	7,457	112.80	97.56	66.40	42.97	417.60	382.53	778.980	1776.300	2,076	906.21
47			3,976	8,922	98.70	161.85	58.10	52.27	365.40	586.18	1001.018	1554.262	1,817	1,243.16
48			3,408	12,092	84.60	210.40	49.80	85.20	313.20	490.17	1223.055	1332.225	1,557	1,604.22
49			3,976	8,170	98.70	124.86	58.10	49.49	365.40	559.16	1001.018	1554.262	1,817	1,243.16
50			3,976	8,083	98.70	100.76	58.10	47.17	365.40	534.86	1001.018	1554.262	1,817	1,243.16
51			3,976	8,172	98.70	111.31	58.10	49.41	365.40	534.84	1001.018	1554.262	1,817	1,243.16
52			3,976	7,025	98.70	126.45	58.10	48.14	365.40	545.78	1001.018	1554.262	1,817	1,243.16
53			3,976	7,623	98.70	111.87	58.10	49.36	365.40	446.06	1001.018	1554.262	1,817	1,243.16
54		**wet seeding**	4,544	7,593	112.80	111.52	66.40	40.18	417.60	383.66	778.980	1776.300	2,076	699.36
55			4,544	7,792	112.80	92.79	66.40	33.84	417.60	382.77	778.980	1776.300	2,076	882.11
56			5,500	5,253	124.67	62.80	76.05	17.00	469.80	234.94	831.569	2983.711	2,336	521.05
57			5,256	6,131	119.13	79.53	72.67	26.91	448.92	305.19	964.178	2851.102	2,232	665.47
58		**transplanting**	9,488	0	158.00	0.00	80.00	0.00	606.00	0.00	0.000	3815.280	2,776	0.00
59			7,392	2,571	144.04	25.02	78.17	6.73	543.97	99.06	252.872	2302.408	2,584	222.34
60			6,758	3,363	139.71	33.03	77.54	8.99	524.84	130.53	330.922	2224.358	2,524	292.63
-		**Maximum**	**9,488**	**12,092**	**158.00**	**214.88**	**80.00**	**91.30**	**606.00**	**709.60**	**0.000**	**3815.280**	**2,776**	**1,604.22**
-		**Median**	**4,487**	**7,707**	**107.63**	**111.69**	**64.48**	**47.53**	**401.94**	**445.87**	**845.591**	**1709.689**	**1,998**	**990.42**
-		**Minimum**	**3,408**	**0**	**83.12**	**0.00**	**49.80**	**0.00**	**313.20**	**0.00**	**1223.055**	**1332.225**	**1,557**	**0.00**