Université de Montpellier II

Ecole doctorale « Systèmes Intègres en Biologie, Agronomie, Géosciences, Hydrosciences et Environnement »
(SIBAGHE)

Propriétés, diversité et variabilité spatio-temporelle des agroécosystèmes

Implications pour leur conception, leur analyse et leur gestion intégrée

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Mémoire présenté pour l'obtention de l'Habilitation à Diriger des Recherches

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Sommaire

I. Résumé des activités de recherche

1. Introduction et trajectoire

J'ai obtenu mon diplôme d'ingénieur agronome en 1997 à l'Université Nationale Lomas de Zamora (UNLZ) (Buenos Aires, Argentine). Depuis – et même auparavant, en tant qu'étudiant-assistant – j'ai été employé dans des activités de recherche à différents niveaux. Pendant les années passées à travailler dans le secteur privé en agronomie, j'ai toujours conservé un contrat à temps partiel à l'UNLZ en tant qu'assistant enseignant et assistant chercheur en agronomie et sciences du sol. En raison de l'arrêt de mon premier projet de thèse pendant la crise économique en Argentine en 2001, j'ai décidé de démarrer un nouveau master à l'étranger (néanmoins, j'ai trouvé les fonds pour finir ma première thèse quelques années plus tard). J'ai obtenu une bourse du gouvernement néerlandais pour poursuivre mes études à l'Université de Wageningen (WUR) aux Pays-Bas. Entre 2005 et 2007, j'ai travaillé comme chercheur associé au *Tropical Soil Biology and Fertility Institute* du Centre International d'Agriculture Tropicale (TSBF, CIAT) à Nairobi (Kenya), en participant à des projets internationaux de recherche pour le développement dans plusieurs pays africains. En 2007 je suis retourné à Wageningen où j'ai obtenu le grade de PhD et où j'ai été employé en tant que chercheur post-doctoral dans le groupe *Plant Production Systems* (PPS). Depuis août 2008 je travaille pour le Centre de Coopération International en Recherche Agronomique pour le Développement (CIRAD), affecté a l'Unité de recherche 102, Systèmes de Culture Annuels du Département Persyst. Dans les sections suivantes, je présente une synthèse de mes activités de recherche passées, la publication et la vie scientifique, et l'encadrement d'étudiants.

2. Publications

Pendant toutes ces années, et à travers mes projets de thèse, des stagiaires et des thésards que j'ai encadré, et des projets internationaux dans lesquels j'ai participé, j'ai mené des recherches sur différents sujets qui ont résulté en 40 publications en revues scientifiques, en 11 publications de divulgation et chapitres d'ouvrages partagés, et en plus de 50 résumés dans des actes du colloques internationaux (voir Annexe 2) ; On peut les regrouper comme suit:

1. Agronomie des cultures maraîchères dans des systèmes intensifs
2. Dynamique du carbone dans l'agro-écosystème
3. Conception et évaluation de systèmes de production agricole durables
4. Gestion de la fertilité des sols dans des systèmes de petits exploitants agricoles
5. Analyses et modélisation des systèmes d'exploitation agricoles à différents échelles

Dans les sections suivantes je présente des exemples des publications concernant chacune de ces rubriques, avec une synthèse des résultats principaux et leurs conclusions.

2.1 Agronomie des cultures maraîchères dans des systèmes intensifs

Deux axes de recherche ont été ciblés dans ce domaine: (1) L'effet de la fertilisation azotée et des conditions de croissance sur le rendement et la qualité des laitues; la préoccupation croissante relative à la qualité nutritionnelle des légumes frais provenant de systèmes de production intensifs, ainsi que les nouvelles règlementations gouvernementales liées à la fois à la pollution par les nitrates des eaux souterraines et la teneur maximum en nitrates des légumes-feuilles frais représentent les principaux axes de cette recherche. Nous avons examiné les stratégies de gestion pour permettre une récolte précoce des laitues frisées tout en maintenant les niveaux de NO_3-N en dessous des seuils critiques. (2) La plupart des légumes tropicaux consommés en Argentine proviennent de systèmes de production de plein air dans la région subtropicale du nord du pays; ils doivent être transportés sur de longues distances (jusqu'à 3000 Km). Les régions tempérées de Pampas ont des étés assez longs pour permettre la culture des poivrons, tomates ou maïs doux en plein air (systèmes beaucoup plus efficients que la culture en serres artificiellement chauffées). Cependant, l'établissement de cultures dans le champ est plus risqué du fait des plus faibles températures dans ces régions, et les cultures doivent être initiées avec des plants de bonne qualité. Notre recherche avait pour objectif d'évaluer des technologies pour la production de plants sur l'exploitation en utilisant les matériaux disponibles, et gérer la fertirrigation pour obtenir des produits précoces, et de qualité.

Exemples de publications:

De Grazia, J., Tittonell, P., Chiesa, A., 2004. Growth and quality of sweet pepper (*Capsicum annuum* L.) transplants as affected by substrate properties and irrigation frequency. Advances in Horticultural Science 18, 181 – 187.

De Grazia, J., Tittonell, P., Germinara, D., Chiesa, A., 2003. Phosphorus and nitrogen fertilisation in sweet corn (*Zea mays* L. var. saccharata Bailey). Spanish Journal of Agricultural Research 1, 103-107.

De Grazia, J., Tittonell, P., Chiesa, A., 2002. Pepper (*Capsicum annuum* L.) transplant growth as affected by growing medium compression and cell size. Agronomie 22: 503 - 509.

Tittonell, P., De Grazia, J., Chiesa, A., 2001. Effect of nitrogen fertilization and plant population during growth on lettuce (*Lactuca sativa* L.) postharvest quality. Acta Horticulturae 553, 67-68.

2.2 Dynamique du carbone dans l'agro-écosystème

Deux axes de recherche ont été ciblés dans ce domaine: (1) La compréhension et la quantification de l'effet des facteurs agronomiques de la séquestration du Carbone en analysant le type de compromis auxquels les agriculteurs doivent faire face en prenant une décision concernant la gestion de leur fonds de ressources naturelles, à la fois à l'échelle de l'exploitation individuelle (p.ex. gestion de la fertilité du sol, labour, alimentation du bétail, fumure) et de la communauté (p.ex. gestion des prairies et forêts communales, réseaux sociaux). Le travail d'Henry et al (2009) au western Kenya constitue une première approximation méthodologique pour la quantification de stocks de C dans le sol et dans la végétation dans les systèmes de subsistance africains. Ces résultats ont permis, par exemple, estimer l'ampleur d'un projet CDM dans deux localités au western Kenya, ou l'effet potentiel du changement climatique sur la séquestration du C dans ces systèmes. (2) La région centrale d'Argentine est le lieu de la transition entre deux grands écosystèmes: les prairies de Pampas et les savanes d'El Espinal. C'est également la zone d'expansion actuelle de la frontière agricole, alimentée par le développement de systèmes de semis direct qui permettent de cultiver sur des sols plus fragiles (typiques des formations forestières d'El Espinal). Les préoccupations concernant la durabilité de ces systèmes indiquent le besoin de développer des indicateurs de suivi, parmi lesquels le C organique du sol a été proposé étant donné sa nature intégrative. L'impact à long terme des régimes de gestion d'utilisation des sols, tentant de comprendre et reconstruire des chronoséquences de C dans le sol ont été analysés en utilisant la modélisation en simulation dynamique. Le modèle CENTURY a été paramétré, puis testé en utilisant les données collectées sur des sites couplés détériorés/non détériorés sous des conditions de formation initiales de sols similaires.

Exemples de publications :

Tittonell, P., Rufino, M.C., Janssen, B., Giller, K.E., 2009. Carbon and nutrient losses from manure stored under traditional and improved practices in smallholder crop-livestock systems – evidence from Kenya. Plant and Soil, accepted: 3/2009.

Henry, M., Tittonell, P., Manlay, R., Bernoux, M., Albrecht, A., Vanlauwe, B., 2009. Biodiversity, C stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agriculture, Ecosystems and Environment 129, 238–252.

Tittonell, P., De Grazia, J., de Hek, S., Bricchi, E., 2006. Exploring land use scenarios by long-term simulation of soil organic matter in central Argentina. Spanish Journal of Agricultural Research 4, 381-389.

2.3 Conception et évaluation des systèmes de production agricole durables

Deux axes de recherche ont été ciblés dans ce domaine: (1) Systèmes de gestion du sol avec des intrants organiques à long terme par rapport à des intrants conventionnels à faible dose en production maraîchère intensive. Des expérimentations avec des rotations de cultures de légumes furent établies et suivies pendant 10 ans pour évaluer l'utilisation de diverses fumures biologiques et animales comparée aux régimes de fertilisation de systèmes avec intrants conventionnels à faible dose. Une des principales contraintes à l'utilisation d'alternatives biologiques était la qualité visuelle des légumes-feuilles. (2) Effet des systèmes de labour et des rotations sur la matière organique des sols (en cours[1]). Des expérimentations à long terme ont été établies en 2006 où les rotations typiques des cultures annuelles (blé, soja, maïs, etc.) sont conduites dans des systèmes de labour conventionnel, réduit ou sans labour (SCV) pour suivre les changements de propriétés du sol, comme la teneur en C et en éléments nutritifs, des propriétés physiques du sol (infiltration, rétention d'eau, compaction), et la performance agronomique des cultures. La modélisation des systèmes de culture et des effets de la succession sont aussi prévus. (3) Evaluation des impacts de différents scénarios d'intégration agriculture-élevage à l'échelle de l'exploitation sur la fertilité du sol et la durabilité des systèmes de production vivrière en Afrique sub-saharienne. L'analyse de recyclage d'azote dans les systèmes culture-élevage intégrés d'Afrique de l'Est et du Sud a été conduit en utilisant des techniques de « *Ecological network Analysis* » provenant de l'écologie et la modélisation de type « *Fuzzy-logic* » pour mieux caractériser l'effet des décisions de l'agriculteur, avec l'objectif de contribuer a concevoir des systèmes de gestion des ressources nutritifs efficients et durables. L'analyse comparative des systèmes culture-élevage intégrés entre ces diverses régions suggère que les producteurs ayant développé des mécanismes de coopération agriculture-élevage les plus perfectionnés ont une meilleure fertilité des sols et des systèmes de production les plus durables. Pourtant, les mécanismes d'intégration ne sont pas les mêmes aux différentes régions, et ils présentent des taux de recyclage et des efficiences d'utilisation de l'azote significativement variables.

Exemples de publications :

Rufino, M.C., Tittonell, P., Reidsma, P., Lopez-Ridaura, S., Hengsdijk, H., Giller, K.E., Verhagen, A., 2008. Characterisation of N flows and N cycling in smallholder crop-livestock systems in the highlands of East and southern Africa using network analysis. Nutrient Cycling in Agroecosystems, in press: doi 10.1007/s10705-009-9256-9.

Rufino, M.C., Tittonell, P., van Wijk, M.T., Castellanos-Navarrete, A., de Ridder, N., Giller, K.E., 2007. Manure as a key resource to sustainability of smallholder farming systems: analysing farm-scale nutrient cycling efficiencies within the NUANCES framework. Livestock Science 112, 273–287.

Moccia, S., Chiesa, A., Oberti, A., Tittonell, P., 2006. Yield and quality of sequentially grown cherry tomato and lettuce under long-term conventional, low-input and organic soil management systems. European Journal of Horticultural Science 71, 183-191.

2.4 Gestion de la fertilité du sol dans les systèmes de petits exploitants agricoles

La fertilité du sol est décrite comme le principal facteur expliquant la diminution de la production de nourriture par habitant en Afrique sub-saharienne. Ceci est particulièrement vrai dans les zones à forte densité de population telles que les hautes terres autour du lac Victoria en Afrique de l'Est. Divers projets dans cette zone ont été conduits pour analyser l'effet de la diversité régionale et socio-économique des ménages sur les pratiques de gestion affectant le statut de fertilité des sols. Des typologies d'exploitations en ont été déduites afin de caractériser la diversité des ménages, puis de les classer. Une telle catégorisation est allée au-delà du classement classique selon la richesse pour inclure les objectifs et les stratégies à long terme des ménages. Les modifications annuelles des stocks en éléments nutritifs dues aux décisions des agriculteurs ont été décrites et quantifiées. Les résultats illustrent comment les agriculteurs provoquent l'hétérogénéité typique au sein des exploitations, souvent connue sous le nom de gradients de fertilité des sols. Les modèles spectraux des scanners NIRS (proche Infra rouge) pour prédire les propriétés du sol ont été calibrés et utilisés pour caractériser les sols. L'importance relative de la fertilité du sol (par exemple, teneur en éléments nutritifs, texture) et les facteurs de gestion (par exemple, la densité de

[1] Des résultats partiels de ce dispositif ont été déjà présentés comme : De Grazia, J., Barrios, M.B., Tittonell, P., Rodríguez, H.A., Andrada, H.I., Fernández, F., 2008. Dinámica del agua en el suelo bajo diferentes sistemas de labranza en una rotación trigo-soja. Congreso Argentino de la Ciencia del Suelo, 13-16 May, San Luis, Argentina.

plantation) dans la détermination du rendement des cultures ont été analysées en utilisant des techniques de ‘Arbres de Classification et de Régression’ (CART), et plusieurs effets synergiques ont été identifiés.

Exemples de publications :

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2009. Yield gaps, nutrient use efficiencies and responses to fertilisers by maize across heterogeneous smallholder farms in western Kenya. Plant and Soil 313, 19–37.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya – an application of classification and regression tree analysis. Agriculture Ecosystems and Environment 123, 137-150.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agricultural Systems 94, 376-390.

Vanlauwe, B., Tittonell, P., Mukalama, J. 2006. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Nutrient Cycling in Agroecosystems 76, 171-182.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment, 110, 166-184.

2.5 Analyses et modélisation des systèmes d’exploitation agricoles à différents échelles

Une grande quantité d'informations est disponible sur différentes approches sur la gestion de la fertilité des sols dans les petites exploitations en Afrique, mais son appropriation et sa mise en pratique sont réduites. En dépit du manque de dissémination et des limitations socio-économiques pour adopter ces technologies, un problème fondamental est le manque d'intégration et d'utilisation d'une telle connaissance par la communauté scientifique. Beaucoup d'informations sur la gestion de la fertilité des sols dérivent de recherches à l'échelle de la parcelle; peu d'études ont comparé la potentialité de combiner des technologies dans une zone ciblée, en considérant les facteurs multiples opérant à l'échelle de l'exploitation et leurs interactions à une échelle supérieure, au sein de villages ou de régions. Les décisions quotidiennes prises par les agriculteurs concernant l'allocation de leurs éléments nutritifs et les ressources en main d'œuvre ont des conséquences sur l'équilibre entre les entrées et les sorties des éléments nutritifs. Par exemple, les champs éloignés de la ferme sont également souvent situés sur de fortes pentes. Donner la priorité aux parcelles près de la ferme implique souvent que les parcelles en pente sont semées plus tard, abordant la saison des pluies avec des sols nus. De telles relations ne sont pas toujours prises en compte pour calculer les équilibres en éléments nutritifs. J’ai participé a la conception des modèles de simulation pour les sous-systèmes de cultures et d'élevage jusqu'aux outils de simulation pour l'analyse des compromis dans l'allocation des ressources à l'échelle de l'exploitation. Quelques exemples de méthodologies de recherche innovante sont: (1) L'utilisation des techniques de modélisation inverse pour optimiser les décisions de gestion à l'échelle de l'exploitation en intégrant l'allocation des ressources en main d'œuvre et financières ; (2) Le lien dynamique des modèles de production des cultures (basés sur la disponibilité en eau, N, P et K), d'élevage (en utilisant des taux de conception stochastiques) et de gestion de la fertilisation (avec des systèmes de "logique floue") à l'aide d'un outil de simulation à l'échelle de l'exploitation pour l'analyse des stratégies de long terme. Je me suis surtout intéressé au développement d'un modèle de production des cultures simple mais déjà robuste, relativement peu exigeant en données, mais suffisamment sensible pour cerner les réponses différentielles au sein d'une exploitation aussi bien que les modifications à long terme de la productivité des sols. Ce modèle, FIELD (*Field-scale Interactions, resource use Efficiencies, and Long term soil fertility Development*), a été calibré et testé dans diverses conditions au Zimbabwe et au Kenya, et il est en train d'être adapté aux systèmes basés sur le mil au Niger, à ceux basés sur le coton au Mali, sur le café dans les hautes terres en Afrique de l'Est et sur le manioc et la banane en Ouganda.
Exemples de publications :

Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N., Giller, K.E., 2009. Beyond resource constraints – exploring the physical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agricultural Systems 101, 1- 19.

Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2008. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya – explorations using the crop-soil model FIELD. Agronomy Journal 100, 1511-1526.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A., Giller, K.E., 2008. Using the crop simulation model APSIM to generate functional relationships for analysis of resource use in African smallholder systems: aggregating field-scale knowledge for farm-scale models. Agricultural Systems 97, 151–166.

Tittonell, P., M.T. van Wijk, M.C. Rufino, J.A. Vrugt, K.E. Giller, 2007. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: a case-study from Kakamega district, western Kenya. Agricultural Systems 95, 76–95.

Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M., Giller, K.E., 2007. Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research, 100, 348 – 368.

3. La vie scientifique et académique

Pendant ces années, j'ai construit un large réseau de collègues dans de nombreuses institutions qui me permet une collaboration fructueuse et une participation à différents projets. Je participe aux consortiums suivants: (i) CIALCA (Consortium International pour l'Amélioration des Moyens d'Existence basés sur l'Agriculture en Afrique Centrale), un réseau de chercheurs des organisations internationales TSBF-CIAT, IITA, INBAP et des organisations nationales de recherche agronomique en Rwanda, Burundi et DR Congo ; (ii) NUANCES (Nutrient Use in Animal and Cropping Systems – Efficiences and Scales), qui regroupe des chercheurs des organisations internationaux CIMMYT, TSBF-CIAT, IRD, CIRAD, ILRI et des organisations nationales de recherche agronomique au Kenya, Ouganda, Tanzanie, Zimbabwe, Zambie, Mali, Ghana et Cameroun.

Je suis souvent impliqué dans des activités d'enseignement et de formation au niveau universitaire. J'ai donnée des cours occasionnellement à l'Université de Wageningen et à SupAgro, Montpellier, mais plus fréquemment j'ai organisé des cours internationaux de niveau de post-graduation sur place, comme au Zimbabwe (Janvier 08), en Rwanda (Janvier 07, Novembre 08), en Argentine (Octobre 08) au Mexique (Mars 09) ou à Cuba (Mai 09). Jusqu'à ce jour, j'ai participé (et participe) à l'encadrement d'un total de 34 étudiants, dont 16 du niveau doctoral[2] (voir Annexe 1). J'ai participé des jurys d'évaluation de thèse doctoral (Un exemple récent : Astrid Marquez, *A systems approach to investigate agricultural intensification processes in Venezuela*, School of Geosciences, University of Edinburgh, May 2008).

Je participe régulièrement à des conférences et à des réunions scientifiques, en tant que présentateur ou organisateur (Un exemple récent : Session chair at the SEAMLESS Conference : Integrated Assessment of Agriculture and Sustainable Development, 10-12 March 2009, The Netherlands). Quand cela est possible, j'accepte les opportunités pour publier dans des revues de vulgarisation pour toucher un public plus vaste, en dehors des cercles scientifiques (Un exemple récente : Tittonell, P., Misiko, M., Ekise, I., 2008. Talking soil science with farmers. LEISA Magazine 24(2), 9 – 11.). Du fait de mon travail passé et actuel, je suis régulièrement invité comme relecteur pour des articles scientifiques dans des revues comme, entre autres, *Agricultural Systems*, *Agriculture Ecosystems and Environments*, *Soil and Tillage Research*, *Ambio, Biological Agriculture and Horticulture, CAB Reviews, Environmental Modelling and Software, African Journal of Agricultural Research, Agronomy for Sustainable Development, Canadian Journal of Soil Science, Plant and Soil*.

[2] Mes activités d'encadrement de thésards, aussi que mon contrat comme post-doc, ont commencée avant obtenir mon diplôme de doctorat. A l'Université de Wageningen j'ai profite d'un régime de doctorat spéciale de courte durée, en vue de mes expériences antérieures en recherche scientifique.

II. Projet de recherche

Propriétés, diversité et variabilité spatio-temporelle des agroécosystèmes – Implications pour leur conception, leur analyse et leur gestion intégrée[3]

Résumé

Les agroécosystèmes multifonctionnels doivent satisfaire les demandes d'une population mondiale croissante, tout en assurant la qualité de l'environnement et une qualité de vie satisfaisante des acteurs. La réalisation des fonctions nécessaires pour satisfaire les services attendus des agroécosystèmes, tout en réduisant au minimum les externalités associées, dépendent en grande partie des décisions stratégiques (conception) et tactiques (gestion) prises par les acteurs qui poursuivent différents objectifs et qui sont impliqués à différentes échelles, dans des jeux de contraintes des milieux biophysiques et des contextes socio-économiques.

Ce projet de recherche vise :
(i) la formalisation et la mise au point de méthodologies pour l'analyse quantitative, l'évaluation et la conception des agroécosystèmes à différentes échelles, avec la prise en considération des spécificités liées à la diversité et à la variabilité spatio-temporelle de ces systèmes;
(ii) à contribuer à la conception d'agroécosystèmes écologiquement intensifs et durables par la mise en place de technologies et de pratiques innovantes, adressées en particulier à des exploitations familiales pour lesquelles l'agriculture représente la source principale de nourriture et de revenus monétaires.

Quatre domaines de recherche sont définis dans cette contribution à l'analyse, à la conception et à la gestion des agroécosystèmes dans leur diversité et leur variabilité spatio-temporelle : (I) L'étude des propriétés et des indicateurs de durabilité des agroécosystèmes, avec un accent particulier sur leur organisation, leur diversité et leur fonctionnement ; (II) La conception de systèmes de culture innovants et écologiquement intensifs ; (III) L'analyse de la durabilité et des services environnementaux attendus des agroécosystèmes ; (IV) L'élaboration de méthodologies pour l'analyse des compromis, opportunités et conflits entre acteurs dans la gestion de ressources naturelles, intégrant les dimensions sociales et écologiques des agroécosystèmes.

Un intérêt particulier est porté sur les propriétés qui se rapportent à l'organisation, à la diversité et à la dynamique des agroécosystèmes, en effet ces propriétés sont déterminantes sur la vulnérabilité et la capacité d'adaptation des communautés rurales. Des indicateurs de la vulnérabilité et de la durabilité des agroécosystèmes seront établis pour caractériser leur variabilité dans l'espace et le temps (domaine I). La structuration de la variabilité et de la diversité sera analysée dans le but de raisonner et optimiser les interventions technologiques et mesures incitatives dans le cadre d'opérations de développement (par exemple, des gradients de fertilité du sol, l'anisotropie des paysages agricoles, la diversité de ménage et de stratégies de vie rural).

L'intensification écologique des systèmes de culture correspond à une plus grande efficience des ressources naturelles (le rayonnement, l'eau, les éléments nutritifs) et sociales (terre, capital et main d'œuvre). Des mesures pour améliorer l'optimisation de l'utilisation des ressources seront explorées (domaine II) avec pour objectif l'intensification durable des productions, à travers notamment la diversification dans l'espace et le temps des systèmes de culture. Une première étape dans la conception de systèmes de culture efficients en terme de ressources, est de porter un diagnostic sur les processus et les facteurs qui rendent le système traditionnel peu efficace (analyse des écarts au potentiel). L'évaluation des causes de la variabilité des rendements obtenus par les paysans et la mise en place d'essais en parcelles

[3] Ce projet de recherche a été conçu en anglais, une langue en laquelle je m'exprime facilement et avec précision. Favorisant un texte approprié en anglais au-dessus d'une traduction pauvre en français, j'ai gardé la section entière décrivant le projet de recherche en anglais. Ce qui suit est un résumé traduit en français.

paysannes sont deux méthodologies que l'auteur de ce projet a appliquées intensivement et qui fournissent des informations de valeur inestimable pour la conception de systèmes par la modélisation et/ou le prototypage.

La capacité d'un agroécosystème à fournir des services est déterminée par ses propriétés intrinsèques, aussi les fonctionnalités attendues doivent être intégrée dès la phase de conception. Les recherches à conduire dans le domaine III visent à comprendre et mesurer le déterminisme de facteurs agronomiques et écologiques sur les fonctions attendues. Sans contredire la définition conventionnelle de la durabilité basée sur des considérations sociales, économiques et environnementales, ce projet de recherches définit les agroécosystèmes durables comme étant ceux qui atteignent des niveaux acceptables pour les différents indicateurs qui les caractérisent (par exemple, efficacité, diversité, stabilité, fiabilité, résilience).

Les agroécosystèmes tropicaux conduits dans des exploitations familiales ont pour caractéristiques leur diversité, leur hétérogénéité et leur dynamique (trajectoire). Ces caractéristiques de systèmes en petit paysannat devraient être prises en compte dès la phase de conception des interventions dans le cadre d'une gestion raisonnée des ressources naturelles. Quand les ressources deviennent moins abondantes et/ou dégradées, comme c'est souvent le cas dans des régions à forte densité de population, les transferts de ressources entre écosystèmes tendent à augmenter, et à créer des situations conflictuelles qui vont à l'encontre d'un équilibre général au niveau du système agraire. Le domaine de recherche IV a pour objectif développer des méthodologies pour l'analyse explicite de tels conflits (*tradeoffs*), en tenant compte de la dimension socioculturelle de l'agroécosystème, l'objectif étant de contribuer à la recherche d'alternatives à ces situations conflictuelles par l'intensification agricole.

Agroecosystem properties, diversity and spatio-temporal variability – Implications for their design, analysis and integrated management

Summary

Multifunctional agroecosystems should meet the demands of an increasing world population, while ensuring environmental quality and viable local livelihoods. Achieving the desirable agroecosystem service functions, as well as minimising their associated externalities, depend largely on strategic (design) and operational (management) decisions taken by agents who pursue different objectives and are involved at different scales, confined by the possibilities offered by the broader biophysical and socio-economic (past and present) environments. This research project aims at:

(i) formalising and fine-tuning methodologies for the quantitative analysis, evaluation and design of agroecosystems at different scales, with special emphasis on studying properties related to their diversity and spatio-temporal variability; and

(ii) contributing to the (re-)design of agroecosystems through the development and testing of innovative technologies and practices, targeting in particular systems managed by rural families for whom agriculture represents their major food and income-generating activity.

Four areas of research are defined within this project that aim at contributing to the analysis, design and management of agroecosystems while embracing their diversity and spatio-temporal variability: (I) The study of properties and indicators of agroecosystems, with emphasis on their organisation, diversity and functioning; (II) The design of innovative, ecologically intensive cropping systems; (III) The analysis of sustainability and environmental service functions of agroecosystems; (IV) The development of methodologies to analyse tradeoffs, opportunities and conflicts in natural resource management systems, embracing the social and ecological dimensions of agroecosystems.

Of particular interest are the properties that relate to the organisation, diversity and dynamics of agroecosystems, as they form the basis to understand the vulnerability and adaptation capacity of rural communities. Indicators of vulnerability and sustainability of agroecosystems will be studied (Area I) in relation to their variability in space and time. Variability and diversity patterns will be described and categorized to aid a better targeting of technology/development interventions (e.g., soil fertility gradients, anisotropy of agricultural landscapes, household diversity and livelihood strategies).

The ecological intensification of cropping systems should aim at improving their efficiency in the use of natural (light, water, nutrients) and social (land, capital and labour) resources. Measures will be explored (Area II) for the sustainable intensification of cropping systems through increased diversification in space and time and better targeting of resources to specific socio-ecological niche. A first step in the design of resource-efficient cropping systems is to understand the processes and factors that render the current system inefficient (yield gap analysis). The assessment of the causes of yield variability on farmers' fields and the establishment of research trials on-farm are two methodologies that the author of this project has applied extensively and that provide invaluable information for systems design through modelling and/or prototyping.

The provision of agroecosystem functions is regulated by their intrinsic properties, which functionality can be influenced by design. The research to be conducted in Area III aims at understanding and quantifying the effect of different agronomic and ecological determinants of such functions. Without contradicting the conventional definition of sustainability based on environmental, social and economic aspects, this research proposal defines sustainable agroecosystems as those that fulfil acceptable levels of different indicators pertaining to their various properties (e.g., efficiency, diversity, stability, reliability, resilience).

The smallholder farms that integrate most tropical agroecosystems are in general highly diverse, heterogeneous and dynamic, and therefore a single recommendation, management plan or policy will not suit all of them. These characteristics of smallholder systems should be considered in the design of interventions to address improved natural resource management. Farmers face tradeoffs in deciding on the management of their natural resource base, both at individual farm and at community scale. When resources become too scarce and/ or degraded, as is often the case in areas of dense human population, agriculture and resource 'harvesting' tend to expand onto adjacent natural ecosystems, obviously conflicting with nature conservation. Research Area IV aims at developing methodologies for the explicit analysis of such tradeoffs, accounting for the influence of the socio-cultural dimension of the agroecosystem, and to propose ways to curtail such trends through agricultural intensification.

1. Introduction and research aims

The integrated management of agroecosystems refers to the set of principles, decisions and practices that propend to achieving the various service functions that are desired/ expected from them. These may include the production of food, fibre and energy, watershed protection and regulation of the local and regional hydrology, conservation of (agro) biodiversity and habitats, carbon sequestration, or the preservation of the rural landscape, local traditional livelihoods and their cultural inheritance. The willingness to achieve two or more of these objectives simultaneously often places decision makers in the face of trade-off situations. Such trade-offs may take place between objectives that are relevant at different scales of intervention or more to certain actors than to others. Frequently, the achievement of one objective may be associated with one or more negative externalities. Less frequent, but yet plausible, are the cases in which synergies between objectives or win-win situations are found.

While management refers to principles-put-in-practice within the realm of operational and/or tactical decision-making, the simultaneous achievement of various agroecosystem service functions requires strategic design. In most cases, however, the designer deals with existing agroecosystems[4] and thus strategies are laid out for their re-design. The *ex-ante* evaluation of the newly designed system allows testing its performance and eventually revising its structure in relation to expected levels of services and externalities. Simulation modelling may have an important role to play in such design-evaluation cycles, through their use in prescriptive studies (projections, predictions, and explorations), scenario analysis or monitoring and evaluation. However, an apparently simple question that is often difficult to answer is: what needs to be modelled? One of the major tasks in this research project is to build-on from the following answer: what needs to be modelled is the behaviour of different indicators that reflect one or more agroecosystem properties of interest.

A model, in the broadest sense of the term, can be defined as a simplified representation of a system to study its behaviour; and the system itself as a limited part of reality containing interrelated elements[5] (Lefelaar, 1999). This limited part of reality, with all its elements and inherent complexity has been defined as an ontological system, a real, tangible one, and its representation as a semiotic system (Uso-Domenech, 2004). Many different semiotic systems may be defined to represent a single ontological system. Such representations may be done using different techniques and languages (e.g. mathematics, in the case of simulation models), they always imply a degree of reductionism, and the final outcome (the model) depends on the observer and its objectives for studying the system. It is to be noticed that such reductionism takes place in any attempt to simplify the real system for its study or intervention, such as when building a mathematical model, designing an experiment in the field, isolating a micro-organism in the laboratory, or when choosing the scale and boundaries of a system or the relevant actors in a multi-stakeholder process.

Further, the simplification of reality to build the semiotic system is normally done by assuming (i) 'average' conditions at which the system can be found, and (ii) modal representations of its structure that disregard the variations in form that may – in reality – describe a continuum. The representativeness of the semiotic system, based on these two assumptions, may be thus threatened by two elements that are certainly inherent to agroecosystems: their diversity and spatio-temporal variability. These two elements not only represent constraints to a good representation of the agroecosystem, but they may also be associated with desirable characteristics that render the system more stable, more reliable or more efficient. Recognising these characteristics of agroecosystems is a pre-requisite to improve the impact of agricultural research for development. The other major task of this research project is thus to propose ways of embracing agroecosystem diversity and variability in space and time into the design of strategies

[4] Among the various definitions available, I refer to agroecosystems following Gordon Conway's (1987): "Agroecosystems are ecological systems modified by human beings to produce food, fibre or other agricultural products", but adding 'services' to the list of agroecosystems outputs. Although the biological complexity of the natural ecosystem may be lost during its transformation, new dimensions of complexity arise in the agroecosystem from the interaction between socio-economic and biological processes.

[5] Interestingly, a well known ecologist as Odum (1985) defines systems as "Groups of parts (or sub-systems) that are interacting according to some kind of process", including the notion of an overall 'process' but excluding the idea of a 'boundary' delimiting the system. When dealing with natural ecosystems, it is difficult to establish their boundaries with some degree of exactitude.

to target technology and management innovations aiming at sustainable development and equity across rural regions.

Meeting the demands of an increasing world population (from 6.5 billons nowadays to more than 9 billons in 2050), while ensuring environmental quality (preservation of habitats and biodiversity, reduced environmental impact of agriculture) and viable local livelihoods poses serious challenges to agricultural research for development. Achieving the desirable agroecosystem service functions, as well as minimising their associated externalities, depend largely on strategic (design) and operational (management) decisions taken by agents who pursue different objectives and are involved at different scales, confined by the possibilities offered by the broader biophysical and socio-economic (past and present) environments. This research project aims at:

(iii) formalising and fine-tuning methodologies for the quantitative analysis, evaluation and design of agroecosystems at different scales, with special emphasis on studying properties related to their diversity and spatio-temporal variability; and

(iv) contributing to the (re-)design of agroecosystems through the development and testing of innovative technologies and practices, targeting in particular systems managed by rural families for whom agriculture represents their major food and income-generating activity.

The various research lines to be developed within this context respond to the mandate and incumbency of the research unit *Systèmes de Culture Annuels* (SCA 102) of the *Centre de coopération Internationale en Recherche Agronomique pour le Développement* (CIRAD), and in particular to the priority research axes of the Team 1, CESCA (*Conception et Evaluation de Systèmes de Culture Annuels*). Although not restrictively, this research project places emphasis in the analysis of smallholder farming systems, which are the main target of this organisation. In presenting the different research lines, examples of currently on-going or recently past research conducted by the author will be used whenever pertinent. A succinct theoretical account and literature references for the main concepts sustaining this project (Section 2) is followed by the definition of the major research lines and a brief description and illustration of each of them (Section 3).

2. Concepts and definitions

2.1 Agroecosystem properties

Systems theory coined a wide array of system properties, of which some are used more or less frequently in analysing social, biological or cybernetic systems (Weinberg, 2002). Agroecosystems are amongst the latter; unlike natural ecosystems, these are systems with well-defined goals. Of all the useful analogies established between ecological and human systems, this research projects follows the conceptualisation proposed by Conway (1987): the goal of an agroecosystem may be defined in the form of increased social value, its boundaries have a social dimension, they can be characterised by a set of dynamic properties that describe their behaviour, and they can be defined as a hierarchy of nested systems at which bottom lay the crop field or the livestock paddock. The agroecosystem properties defined by this author were productivity, stability, sustainability and equitability. Later theoretical work used these concepts to re-define sustainability at the core of multiple dimensions and properties (Lopez-Ridaura et al., 2002). According to this view, productivity, stability, reliability, adaptability and resilience are all attributes of sustainable agroecosystems, from which relevant indicators can be identified.

System properties, with particular reference to agroecosystems, will be grouped in two main types: (1) those that reflect the behaviour of the system depending on its own internal structure and functioning, and (2) those that reflect its behaviour in the face of changes in any external or exogenous variable driving or influencing the system. This implies that the study of the properties of a system starts from its structural and functional characterisation, identifying and describing the links between structure and function (or between pattern and function, for certain system types). The various elements that constitute the definition of a system (scales, hierarchies, detail, boundaries, components, interrelations, inputs/outputs) and the study of its behaviour (dynamics, functions, purpose) represent different steps in systems analysis. In other words, analysing a system is building a formal representation of it to study its properties. While agroecosystems diversity may be assimilated to systems properties grouped in type 1 (structural), their spatio-temporal variability is associated with both structural and functional (behavioural, type 2) properties.

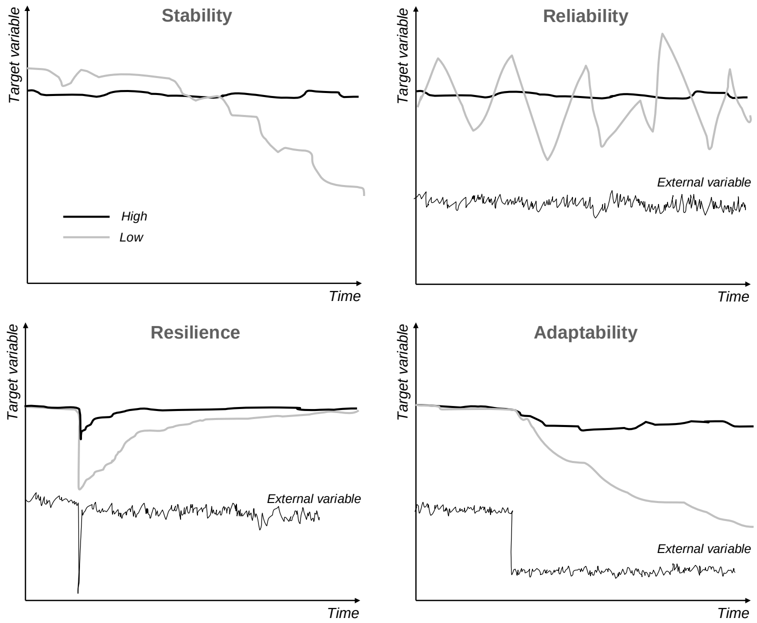


Figure 1: The theoretical curves represent the evolution of a certain target variable (e.g., an indicator of agroecosystem productivity) in time. Stability refers to the capacity of the system to ensure the same level of the target variable, albeit normal oscillations, over the period of time considered. In this definition, stability depends on the systems' own structure; loss of stability in an agroecosystem may take place due to soil nutrient depletion, for example. Reliability, resilience and adaptability are properties of the system in relation to the behaviour of an external driving variable. In the face of normal oscillations in the latter, an unreliable system will exhibit large variability in the level of the target variable over time. When there is a shock due to a sudden but temporary change in the level of the external driving variable, a resilient system will recover the level of the target variable faster than an un-resilient one (and may be also less affected by the initial shock, more resistant). When there is a permanent change in the level of the external variable, which may be abrupt (as in the figure) or more gradual, a non-adaptable system exhibits an irreversible decline in the level of the target variable over time. (Schemes adapted from Masera et al., 1999)

The properties of agroecosystems targeted in this project include productivity (efficiency), stability (constancy), reliability, adaptability and resilience (Figure 1). The latter three are properties of type 2, i.e., they describe the response of the system in the face of changes in an external driving variable. These properties are also closely related to agroecosystem vulnerability, often defined as a property that depends on a system's exposure to an external hazard and its inherent sensitivity (Luers, 2005). Two other properties targeted hare are diversity, complexity and organisation, which serve to characterise the structure of the agroecosystem (type 1). In accordance with the definition of agroecosystems adopted here (cf. Conway, 1987), viewed as multi-level hierarchies of nested systems, indicators of diversity, complexity and organisation must be defined for each different scale of analysis. This definition, however, may not be easily married with that used in the classical French school of agronomy (c.f. Dore et al., 2006); attempts to homologate both are briefly discussed in the following section.

Diversity, in its widest sense, comprises the diversity of livelihood strategies in a certain location, diverse land use, management and marketing strategies, the integration of production activities (e.g. crop-livestock interactions), the association of crops and crop cultivars in space and time, or the maintenance of genetic agro-biodiversity in the system. The efficiency in the utilisation of natural, economic and social resources in agroecosystems – which particularly in smallholder agriculture goes far beyond the partial use efficiency of a certain input – relies on one or more of these diversification strategies. The term biodiversity, *senso stricto*, was first used by Dasmann (1968) to refer to the variation of life forms within an ecosystem, biome or the planet. Gaston and Spicer (2004) defined it as the total number of genes, species and ecosystems in a given region. Agro-biodiversity may be seen as a subset of general biodiversity, encompassing all forms of life relevant to agriculture: crops and livestock, semi-domestic and wild plants, soil fauna and microorganisms (Brookfield et al., 2003). A wider definition may include also the diversity of local agricultural practices and rural knowledge.

Knowing the structural diversity of a system may not suffice to explain its behaviour; the way in which the diverse components of the system relate to each other should also be known. Indicators of complexity and organisation were derived from communication science and first used in economics by Leontief (1951, 1966), and later introduced into ecology by Hannon (1973). Indicators such as average mutual information (AMI) and ascendency (A) were proposed by Ulanowicz (1997, 2004) to characterise the development capacity (in terms of increased organisation) of ecological systems, and used recently in comparative analysis of agroecosystems (Rufino et al., 2009a). An indirect measure of organisation of an agroecosystem is its energy and entropy balance. Svirezhev (2000) proposes the use of such concepts of thermodynamics to assess the sustainability of agroecosystems, based on the principle that an ecosystem in equilibrium with its environment has a certain 'capacity' to absorb anthropogenic stress that is regulated by its capacity to expel entropy back towards the environment (the 'entropy pump'). This capacity, which emerges from different agroecosystem properties, can be used to characterise agroecosystems health.

Most of the properties mentioned above are, of course, simultaneous and often interdependent; e.g., a diverse and stable system may at the same time be considered reliable, adaptable or resilient. Objections to this rather normative definition of system properties are not few, particularly because measurements of indicators taken in real agroecosystems rarely reproduce the neatly-drawn theoretical curves in Figure 1. In the words of MacArthur (1968), "Ecological patterns, of which we construct theories, are only interested if they are repeating […] in space and time […], and yet these general events and patterns are only seen by ecologists with a rather *blurred vision*. The very sharp-sighted always find discrepancies and are able to say that there is no generality, only a spectrum of special cases". Such blurred vision, which should not be confused with compromise scientific rigour (Grime, 1979), refers to the capacity to recognise that which is general, important and enduring. Far from being postulates of new theory, these properties are proposed here as operational, working concepts.

2.2 Hierarchies, scales and actors

When agroecosystems are defined as a nested hierarchy of systems (e.g. Fresco and Westphal, 1988) it is necessary to define clearly the various integration levels to be targeted with research and design. Figure 2 attempts to conciliate this approach with the classical nomenclature used in francophone research to refer to the various levels of integration relevant in agriculture. The latter are more closely associated to the spatial than to the temporal scale. However, since most of the agroecosystems properties to be analysed (e.g., modelled, monitored) depend on their dynamics, the relevant temporal scale for each integration level should be also indicated. Agroecosystems can hardly be defined at scales smaller than the plot or larger than a country[6]. Under the definition adopted in this research project, aggregating in space or prospecting in time are not synonymous with up-scaling if they are not done both at the same time. Each integration level must be analysed at its relevant spatio-temporal scale in accordance with the research questions posed.

A number of crop plots and their sequencing in time constitute a cropping system (de Wit, 1992); this could be assimilated approximately with the concept of '*Système de culture*' used in francophone research, except that the latter often refers to the scale of a single plot ("*la parcelle […] l'ensemble du peuplement végétale et le milieu physique, chimique et biologique sur lequel l'homme agit pour en obtenir une production*" – Sebillote, 1977). Cropping systems are nested within farming systems (*Systèmes de production*) together with the other production activities of the farm. In certain agroecosystems, this level may be comparable to 'the crop-livestock system' (Thornton and Herrero, 2001). The integration levels corresponding to the household and the livelihood (e.g. Giller et al., 2006) are more difficult to assimilate to the francophone terminology. They may be defined as '*Systèmes d'activités'* or, more generally as '*Moyens d'existence*', lying in a scale somewhere in between the farm system and the village. The

[6] There are obvious exceptions to this generic statement. For example, the Great Chaco region of South America comprises large areas of Argentina, Paraguay, Bolivia and Brazil. However, many different agroecosystems may be identified within this region, which encompasses a range of annual rainfall from 400 to more than 1500 mm.

‘*Terroir*’ is an entity that, at least in African family agriculture, may be associated with the set of communally owned and shared natural resources (cropping fields, grasslands, woodlands and water sources) (e.g. Prudencio, 1993). This level of integration is more difficult to identify in the densely populated highlands of East and Central Africa, where communally owned resources are virtually extinct. In these cases, the most relevant unit of integration is often the landscape, the toposequence, or the micro-catchment (e.g., Tittonell et al., 2005).

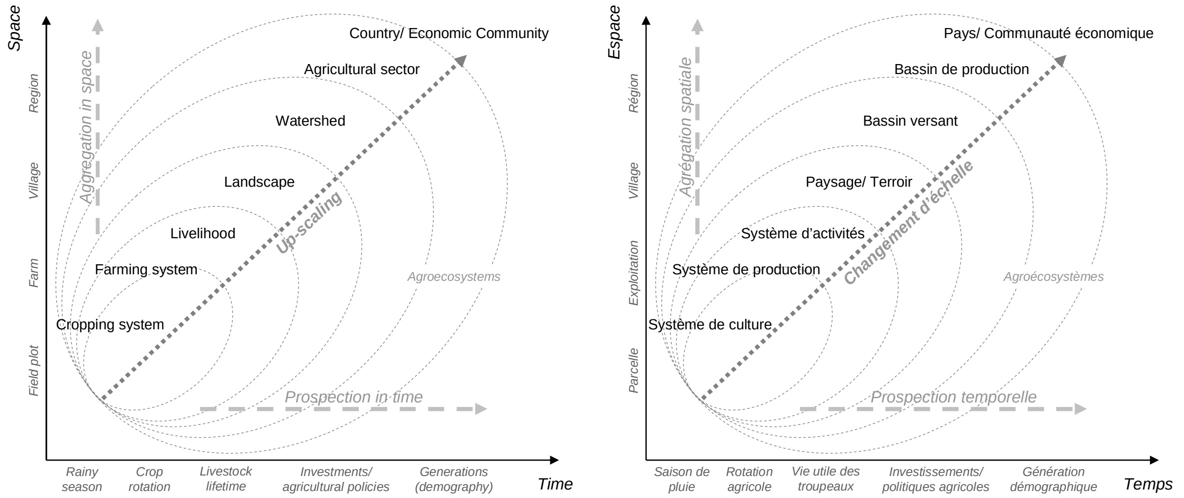


Figure 2: Integration levels at which agroecosystems are defined and their correspondence with the definitions used by French school of agronomy. The minimum spatial unit of an agroecosystem is a crop plot or a livestock paddock. A cropping system is the combination of crops in space and time, while the farming system is the combination of all farm production activities (crops, livestock and non-farm activities). The farm household integrates family labour, consumption, expenditures and the different sources of income (livelihood level). The village and landscape levels may or not coincide depending on the particular land tenure system and the organisation of the rural space (in African family agriculture the *terroir villageois* represents a unit of communally shared resources). In certain cases, the relevant levels of integration are represented by a watershed or a region and, in the domains of policies and markets often the level of integration includes countries, continents or economic communities.

Each integration level has a certain degree of correspondence with a certain spatial scale, an organisational entity (decision-making/ governance) and a temporal horizon (Figure 2). At each scale the type of agents that hold a stake in agroecosystem management and design differs, and the number of relevant actors increases while scaling up. Agroecosystems are complex socio-ecological systems, with biological and cultural dimensions. The impact of human agency through management of natural resources often overrides the net effect of major biophysical processes. Thus, when scaling-up from soil/crop/animal processes or their interaction at plot scale, to the levels of farm household, village or region, the interaction between biophysical and socio-economic processes cannot be ignored. Some go as far as suggesting that human belief systems should be integrated as a major component of human ecosystems (Stepp et al., 2003). Frequently, decision-making on agroecosystem management responds to rules and traditions established by agents that compete for/ negotiate over the use of communally owned resources.

In complex, dynamic and spatially heterogeneous systems interactions take place across spatio-temporal scales that lead to emergent properties and self-regulatory mechanisms (Holling, 1973). Often different buffering mechanisms operating at village scale emerge from collective action (Meinzen-Dick et al., 2004). Next to regulatory feedbacks that may prevent smallholder systems from collapsing, farmers adaptive capacity and alternative strategies (e.g. through rural-urban connectivity – Andersson, 2001) play a major role in systems resilience. In analogy to the concept of informal economies (de Soto, 2000), such alternatives represent informal resource flows, as they are often unaccounted for in farming systems analysis. A key step to understanding adaptation strategies is the study of the local perceptions and knowledge sustaining different mechanisms of indigenous resilience, particularly at the scale of the landscape and its functionality.

2.3 Design, evaluation and ecological intensification of agroecosystems

The challenge of designing innovative agroecosystems demands a close articulation with research activities. Reality (the ontological system) provides research questions constantly, by posing ‘problems’ that require new design (Figure 3). The process of design synthesises knowledge generated by research to arrive at strategic decisions that contribute to changing realities. Unlike on the analytical pathway, where the study of a system’s structure and functioning may contribute to revealing its purpose, the purpose of the new system to be designed is known *a priori*. This dictates which functions should be integrated in the new system and which structures are needed to provide such functions. The continuous evaluation of existing agroecosystems reveals problems and research questions to be addressed, most of which aim at their eventual (re-)design.

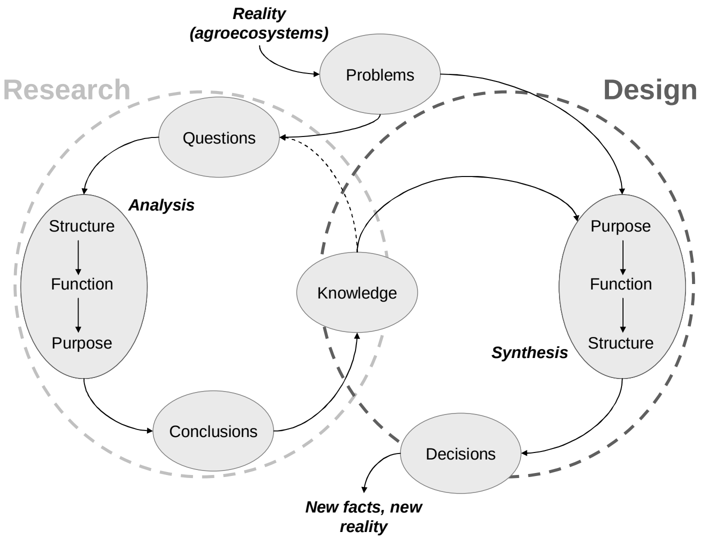


Figure 3: Scheme illustrating the conceptualisation of the terms research and design adopted in this research project, based on the ideas of Goewie (1993). See text for explanation.

The ecological intensification of agroecosystems, as originally defined by Cassman (1999), aims at satisfying the anticipated increase in food demand due to world population growth while meeting acceptable standards of environmental quality and minimizing the expansion of cultivated areas. The basic idea is to reduce the gap between the current and potential yields of major food crops in different agroecosystems, by making an efficient use of naturally available resources and applied inputs, soil quality improvements and precise management of all production factors in space and time. The challenges for research on basic plant physiology, soil science and agroecology[7] are undeniable. Innovative cropping systems must be designed that rely on principles of the integrated management of soil fertility (e.g., Vanlauwe et al., 2002), of weeds, pests and diseases (e.g., Pickett et al., 1997), on soil-conserving techniques such as mulching, minimum or no tillage (e.g., Roose and Barthes, 2001), on association of plant species in space and time (e.g., Kho, 2000), and that exhibit less vulnerability to climatic and/or market variability.

The ecological intensification is thus by no means synonymous with an ecological agriculture. However, the challenge of a more productive-while-less-polluting agriculture necessarily implies that agroecosystem design should aim at capitalising the ecological processes at a maximum, to render the system more efficient and less dependent on external inputs. The redesign of agroecosystem towards more sustainable configuration often involves its diversification. This has been the case in Cuba, were small and medium scale farmers tended to diversify their production systems in response to their lack or limited access to

[7] Although the term agroecology has been used by authors such as Altieri (1999) or Gliessman (1997) to refer to sustainable and/or organic agricultural practices, the term is used here to refer to the scientific discipline that studies agroecosystems (as much as the focus of ecology are the ecosystems).

agricultural inputs to sustain productivity (Figure 4). An intensive monitoring of a number of farms during the years of their transition revealed that the diversified systems were energetically more efficient, less dependent on external inputs, more productive, adaptable and resilient (Funez-Monzote et al., 2008).

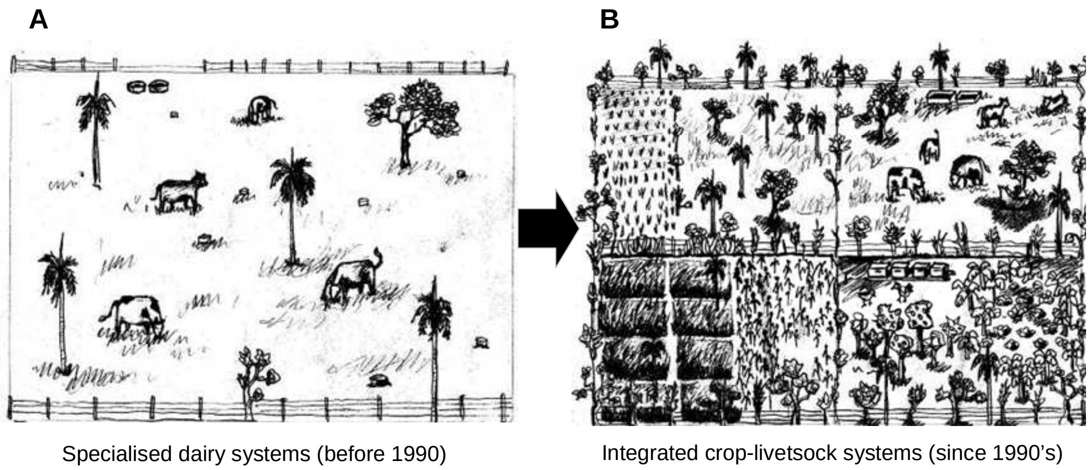


Figure 4: Illustration of the diversification process that took place on Cuban dairy farms after the collapse of the Soviet support and the energetic crisis on the island during the 1990's. Diversification was the spontaneous response of medium to small scale farmers to the lack of agricultural inputs, as documented through longitudinal farm surveying (modified from: Funez-Monzote et al., 2009).

Next to food, fibre and energy production, ecologically intensive agroecosystems are expected to provide ecosystem services. Kremen (2005) classified the various ecosystem services defined in the Millennium Ecosystem Assessment (2003) according to their functionality, into two major groups: supporting (e.g., nutrient cycling, aboveground net primary productivity, or mineralisation and decomposition) and regulating services (e.g. carbon storage, pest and disease control, water flow regulation, or weed invasion resistance). For each specific service one or more service providers may be identified (e.g., trees, vertebrates, soil microbial communities) and indicators of their efficiency postulated (e.g., biomass accumulation rate in trees for C storage; process rates of nutrient cycling, leaching and mineralisation).

Identifying indicators – and their meaningful thresholds – is an important step in agroecosystem design, particularly when optimisation models are used to support this process. Such indicators may be expressed as objectives in multiple criteria and multi-scale analyses, representing the goals of different stake holders (e.g. Herrero et al., 1999), or followed in time to study functional (type 2) properties of the newly designed agroecosystem (e.g. Tittonell et al., 2009a). The definition of meaningful indicators and thresholds allows also for the negotiation and participatory prototyping of desired agroecosystem functions. Negotiation and discussion are of particular importance in the presence of tradeoffs between objectives, and trade-offs mapping with the aid of model exploration (as illustrated in Figure 5) is one of the methodologies that form the basis of 'discussion support systems' (van Keulen, 1995).

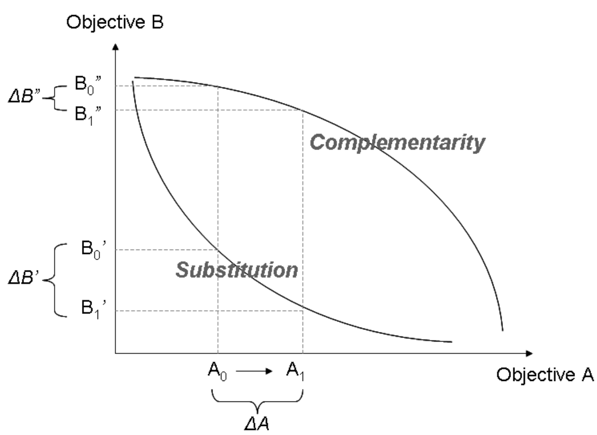


Figure 5: Schematic representation of possible trade-offs between two objectives (A and B). Situations of complementarities or of strong substitution between objectives may be encountered. A change of a certain magnitude in the value achieved for objective A (*ΔA*, from A_0 to A_1) may imply a relatively large (*ΔB'*) or a relatively small (*ΔB"*) 'sacrifice' in the value achieved for objective B, respectively.

Several approaches using models as discussion support tools to enhance participatory learning and action were developed worldwide and using different type of models. The Companion Modelling Approach (Busquet et al., 1999) is one of them, which combines participatory tools such as role playing games with the simulation of the interaction between actors in a community using agent-based modeling techniques. These types of tools are well suited to analyse conflicts and compromises between the social and ecological dimensions of agroecosystems (e.g., in human-nature conflicts such as forest encroachment, drainage of wetlands for cultivation, biodiversity and habitat degradation, etc.).

The type of future-oriented or *ex-ante* studies to be used in agroecosystem design and evaluation may be classified based on two criteria (van Ittersum et al., 1998): their degree of uncertainty and the degree of causality that is known on the processes being studied. Uncertainty is often associated with the time horizon of the scenarios analysed (e.g., 'what is likely to happen next year' vs. 'what if the world oil market collapses in 20 years'). According to this classification, when uncertainty is low, but little is known about the relevant causes and effects governing key phenomena (e.g., when an empirical function is used), the study is defined as a projection. Still under low uncertainty, but when causality increases (e.g., when using a mechanistic, process-based model), the study is defined as a prediction. When using a mechanistic, high-causality approach to study scenarios of large uncertainty, the study is defined as an exploration. Finally, when analysing highly uncertain scenarios using empirical, descriptive tools we may be in the presence of a speculation.

3. Proposed research areas

Four areas of research are defined within this project that aim at contributing to the analysis, design and management of agroecosystems while embracing their diversity and spatio-temporal variability. Each of them contains several research lines. The first area deals with properties and indicators of agroecosystems, with emphasis on their organisation, diversity and functioning. The second area targets the design of innovative, ecologically intensive cropping systems, and the third one the sustainability and environmental service functions of agroecosystems. The fourth research area targets methodologies to analyse tradeoffs, opportunities and conflicts in natural resource management systems, embracing the social and ecological dimensions of agroecosystems at different scales. The four research areas and their integration levels, scales, and methodologies are presented in Table 1.

Table 1: Research areas to be targeted in this project and their main integration level of incumbency, spatial scales, and methodological tools

Research area	Main integration levels	Spatial scale	Tools and methods
I. Indicators and properties of agroecosystems	Cropping systems to agricultural sectors	From plot to region, country	Data meta-analysis Dynamic modelling Surveying and field measurements
II. Design and evaluation of ecologically intensive cropping systems	Cropping systems	Plot(s)	Field experiments Crop-soil modelling On-farm testing/ adaptation
III. Sustainability and ecological services of agroecosystems	Cropping systems to watersheds, agricultural sectors	Plot, farm, landscape, region	Field measurements Monitoring and evaluation Dynamic modelling Data meta-analysis
IV. Tradeoffs, opportunities and conflicts in natural resource management systems	Production systems (crop-livestock), livelihoods, communally shared areas, watersheds, buffer zones of natural reserves	Farm, village, territory, region	Farm- and village-scale bio-economic modelling Surveying and field measurements Participatory research and prototyping Agent-based modelling

The following sections elaborate further, though briefly, on each of these four areas, presenting examples of research questions, methodologies and on-going research. In view of the strategic nature of this research project (i.e., research questions to be explored during the next 10 to 15 years), the objectives pertaining to each research area were expressed as generically as possible, without circumscription of cropping system types or specific locations. The main focus of this research, however, remains on small to medium scale farming systems.

3.1 Indicators and properties of agroecosystems – Organisation, diversity and functioning (Area I)

This research area will tackle the following generic objectives:
(i) To develop/ refine methodological tools for the analysis and monitoring of structural and functional agroecosystem properties by means of indicators
(ii) To study the relationship between agroecosystem properties and their performance in terms of productive and environmental service functions
(iii) To analyse the role of different categories of variability and diversity on the functioning of agroecosystems and their implications for the design of interventions

Of particular interest are the properties that relate to the organisation, diversity and dynamics of agroecosystems, as they form the basis to understand the vulnerability and adaptation capacity of rural communities (e.g., in the face of climatic change, on new demands for agricultural resources such as biofuels, etc.). Indicators of vulnerability and sustainability of agroecosystems (e.g., vulnerability surfaces, entropy balances) will be studied in relation to their variability in space and time. Variability and diversity patterns will be described and categorized to aid a better targeting of technology/development interventions (e.g., soil fertility gradients, anisotropy of agricultural landscapes, household diversity and livelihood strategies). The following paragraphs discuss some examples.

Table 2: Some of the indicators used in the network analysis of N flows in agroecosystems of the highlands of East and Southern Africa by Rufino et al. (2009)

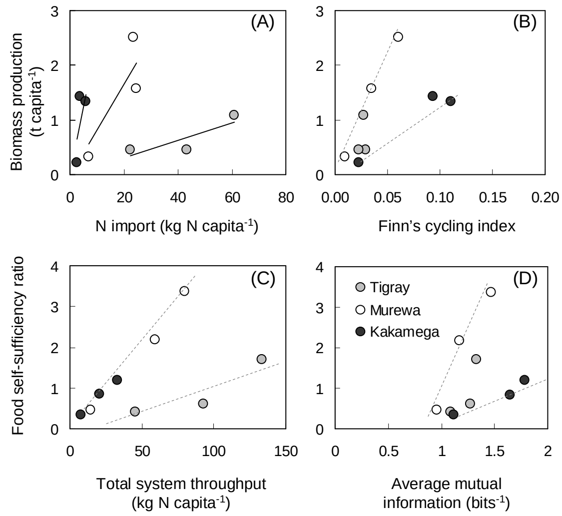
Indicator	Calculation	Reference
Indicators of network size, activity and integration		
Imports	$IN = \sum_{i=1}^{n} z_{io}$	
Total Inflow	$TIN = \sum_{i=1}^{n} z_{io} - \sum_{i=1}^{n} (\dot{x}_i)_-$	Finn (1980)
Compartmental Throughflow	$T_i = \sum_{j=1}^{n} f_{ij} + z_{io} - (\dot{x}_i)_-$	
Total System Throughflow	$TST = \sum_{i=1}^{n} T_i$	
Total System Throughput	$T.. = \sum_{i,j=1}^{n} T_{ij}$	Patten and Higashi (1984)
Finn's Cycling Index	$FCI = \frac{TST_c}{TST}$	Finn (1980)
Dependency	$D = IN / TST$	
Indicators of organisation and diversity		
Average Mutual Information	$AMI = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T..} log_2 \frac{T_{ij} T..}{T_{i.} T_{.j}}$	Ulanowicz (2001), Latham and Scully (2002)
Statistical uncertainty (Diversity)	$H_R = -\sum_{j=0}^{n} \frac{T_{.j}}{T..} log_2 \frac{T_{.j}}{T..}$	

Notation: z_{io} are N inflows to each system compartment (H_i) from the external environment, x_i represents the change in storage of a compartment and f_{ij} represents internal flows between compartments (e.g., from H_j to H_i)

The organisation of agroecosystems (nutrient cycling efficiencies, information flows, energy balances) will be studied using network analysis techniques. Rufino et al. (2009a) describe a first application of this methodology to the comparative analysis of N flows and food self-sufficiency between smallholder crop-livestock systems of Ethiopia, Kenya and Zimbabwe. The main hypothesis behind the use of these indicators is the fact that agroecosystems conserve properties of the natural ecosystems for which these indices were derived. Farm systems are conceptualised as networks, in which the household and the farming activities represent the compartments and the N flows the connections between compartments. In the referred example, indicators assessing network size, activity, cycling, organisation and diversity of the N flows (Table 2) were compared with indicators of productivity and household food self-sufficiency.

The results of this exercise revealed that although the amounts of N cycled were small and comparable at all sites (< 2.5 kg N capita-1 y-1), resource use efficiency and dependency on external resources differed widely between these apparently 'comparable' agroecosystems (Figure 6). System performance was positively related to N flow network size, its organisation and N cycling. These findings contribute to hypothesise that an increased organisation of resource cycling within resource-limited agroecosystems may render the systems more adaptable, less vulnerable.

Figure 6: Biomass production plotted against (A) N imports and (B) Finn's cycling index for farm households of different type at three different sites: Tigray (Ethiopia), Murewa (Zimbabwe) and Kakamega (Kenya); and food self-sufficiency, (calculated as the ratio of food produced on farm per capita divided by the average energy needs of the farm household member) plotted against (C) Total system throughput (T..) and (D) Average Mutual Information (AMI), for the same farm households



Agroecosystem vulnerability and adaptation capacity will be assessed computing 'vulnerability surfaces' as proposed by Luers (2005). The method is based on disaggregating the problem into measures of sensitivity and exposure (x axis), the state of the system relative to a reference threshold (y axis) and a third dimension that represents a vulnerability index (z axis). The main value of the analysis is that it provides a *quantitative* measure of vulnerability that allows comparing alternative agroecosystem configurations and analysing scenarios. The problem, however, resides in establishing the relevant indicators and thresholds for the analysis. Preliminary results form on-going research (Tittonell and Corbeels, unpubl.) indicate the importance of selecting meaningful thresholds, which may be established through the participation of the community, through the use of modelling, historical data, etc. Figure 7 illustrates an example of vulnerability analysis of maize-based agroecosystems in semi-arid Zimbabwe.

Agroecosystem diversity and spatial variability will be categorised through the development of system (farm, field) typologies and classification trees to aid decision-making and design of targeted interventions. Farm system typologies based on resource endowment, production objectives and systems dynamic (farm development cycles) were proposed for smallholder farms in the highlands of western Kenya (Tittonell et al., 2005) and later expanded and tested across smallholder systems of East Africa (Tittonell et al., 2009b). The approach combines field observation and surveying with multivariate statistical techniques. Current research (Tittonell & Giller, unpubl.) aims at generalising a typology of smallholder farming systems across sub-Saharan Africa, identifying relevant thresholds to inform policy and development efforts.

The use of classification and regression tree (CART) analysis for agricultural applications is incipient (e.g., Shepherd and Walsh, 2002; Martius, 2004) but promising. CART analysis is widely used in medical science to produce diagnosis from a set of loosely correlated symptoms (e.g., Crichton et al., 1997). Its application as a diagnosis tool to identify and categorise patterns of variability in agroecosystems (e.g., responsive or non-responsive fields) is a target research field for this project. The potential of this method may be reinforced through its combination with the progressive calibration of less costly, rapid and often remotely sensed diagnosis tools such as the use of near and mid infrared spectral reflectance to characterise soil quality (e.g., Tittonell et al., 2008a). CART is potentially suitable for the analysis of heterogeneous, multi-functional landscapes, linking patterns of landscape anisotropy (niches) to agro-ecological services. On going research in smallholder, sugar-cane based cropping systems of Kenya (Moraine, Clouvel & Tittonell, unpubl.) is already surveying local perceptions of the rural landscape to document the rationale in the spatio-temporal organisation of the agroecosystem.

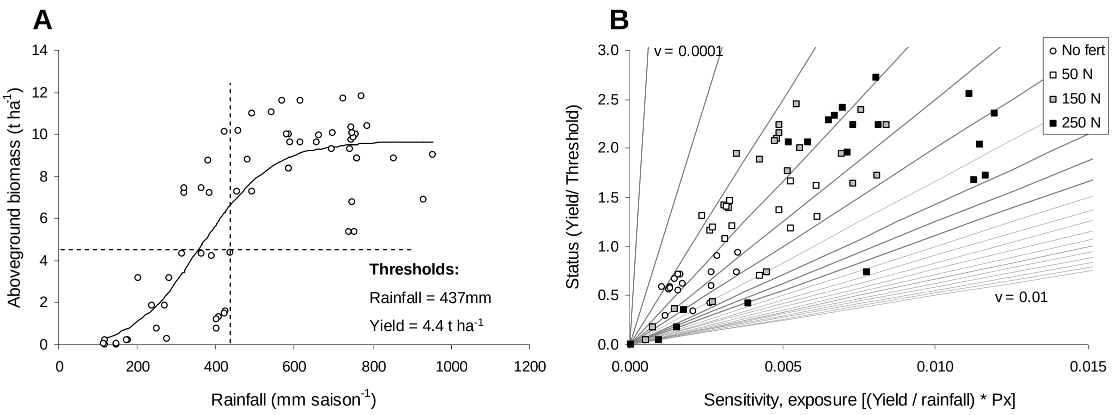


Figure 7: Preliminary results from a vulnerability assessment of maize-based agroecosystems to rainfall variability in Makoholi, Zimbabwe, using the concept of 'vulnerability surface' proposed by Luers (2005). Long term experimental data (A) has been used to establish empirical relationships between rainfall and biomass yields of maize; visual examination of the data distribution indicated threshold biomass yields of 4.4 t ha^{-1}, when the seasonal rainfall is less than 437 mm. A crop simulation model calibrated against these data allowed simulating scenarios of fertiliser application to maize. Such simulations were used to calculate the resulting vulnerability of maize production to rainfall (B) under different N management regimes. The grey lines in panel B should be read as contour lines in a relief map, with vulnerability (v) increasing towards the lower-right corner of the graph. These preliminary results indicate to what extent large doses of N fertilisation may render this system more vulnerable to rainfall (Tittonell and Corbeels, unpubl.)

3.2 Design and evaluation of ecologically intensive cropping systems (Area II)

This research area will tackle the following generic objectives:
(i) To contribute to the design, adaptation and testing of innovative agricultural practices and strategies for the ecological intensification of agroecosystems
(ii) To indentify the main (yield-limiting and yield-reducing) factors responsible for the gap between current and attainable crop productivity and measures to curtail their effect
(iii) To analyse the role of diversification of the cropping systems in space and time in providing the necessary ecological services to maximise resource use efficiency and minimise externalities

The ecological intensification of cropping systems should aim at improving their efficiency in the use of natural (light, water, nutrients) and social (land, capital and labour) resources. This research area will explore measures for the sustainable intensification of cropping systems through increased diversification in space and time and better targeting of resources to specific socio-ecological niches[8]. Resource use efficiency is conceptualised as the product between the ability of the cropping system to capture (explore, intercept, absorb) resources and to convert them into products of interest:

Productivity = Resource availability x Resource capture x Resource conversion

A first step in the design of resource-efficient cropping systems is to understand the processes and factors that render the current system inefficient. The assessment of the causes of yield variability on farmers'

[8] The concept of a multi-dimensional 'socio-ecological niche' to which technologies should be targeted has been used to design the promotion of legume-based technologies in smallholder African systems by Ojiem et al. (2006).

fields and the establishment of research trials on-farm are two methodologies that the author of this project has applied extensively (e.g., Tittonell et al., 2007a; 2008b; Vanlauwe et al, 2006; Misiko et al, 2008; Fermont et al, 2008; 2009; Ebanyat et al., 2009) and that provide invaluable information for systems design through modelling and/or prototyping. These activities have also contributed to analyse yield gaps and indicated that soil variability, typical of smallholder farming systems of East Africa, affects resource use efficiency operating mostly on the efficiency of resource capture. Figure 8 illustrates with a simple scheme the importance of considering spatial soil variability in the form of 'soil fertility gradients' to ensure efficient use of resources, overcoming the failures of 'blanket recommendations'. However, ecologically intensive management goes far beyond the efficient targeting of nutrient inputs; there is also ample room to narrow yield gaps through basic agronomic management (Figure 9).

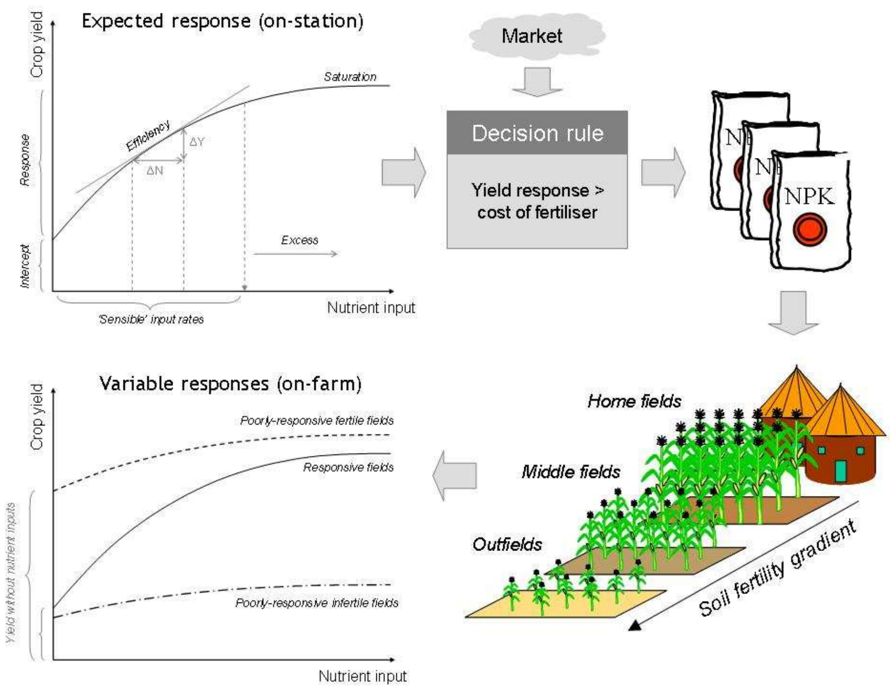


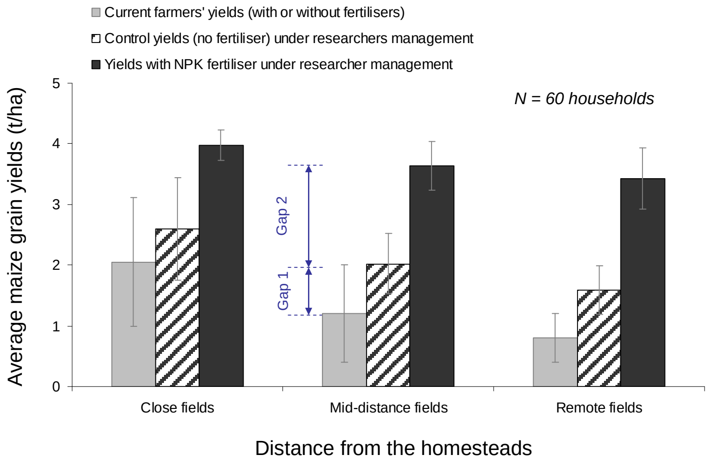
Figure 8: An example of moving from on-station trials to decision rules for niches of soil fertility on heterogeneous farms. Fertiliser experiments provide information on crop responses to nutrient inputs. Based on this, a range of 'sensible' input rates can be identified that ensure biophysically efficient input use, avoiding negative externalities to the environment. Theory indicates that the amount of inputs to be added depends on the balance between necessary investments and economic returns (both affected by market conditions). However, adding nutrient inputs may result in highly variable crop responses across spatially heterogeneous farms. In smallholder farms as small as 0.5 ha 'field types' can be identified that are: poorly responsive fertile fields (normally the home fields), responsive or poorly responsive infertile fields (normally the outfields). For an efficient use of nutrient inputs, these should be 'targeted' to the most responsive fields of the farm. For example, fertile home gardens may be managed with 'maintenance fertilisation', whereas poor fields should be rehabilitated with long-term additions of organic matter before they can response to nutrient inputs. This means also that the impact of input use should also be analysed considering time horizons longer than a single season. (Read more: www.africanuances.nl)

Innovative cropping systems should not only be well performing by themselves, but also well integrated within the wider farming and livelihood systems. Technologies that may be promising from a biophysical point of view may be ignored by farmers when their implementation is incompatible with the broader system they manage. This is often the case with conservation agriculture in Africa, because of its greater demand of labour for weeding or of crop residues to be used as mulches (where they represent the main source of livestock feed during the dry season) (Giller et al., 2009). Research conducted in this area will also contribute to informing the current investments in agricultural productivity in Africa, led by the AGRA[9] consortium (www.agra-alliance.org); some of the main bets of this initiative include the integrated management of soil fertility, greater access and more efficient use of water, the dissemination of

[9] AGRA: Alliance for a Green Revolution in Africa

biological N-fixation and improved legume germplasm, and the intensification of traditional food security crops (e.g., cassava).

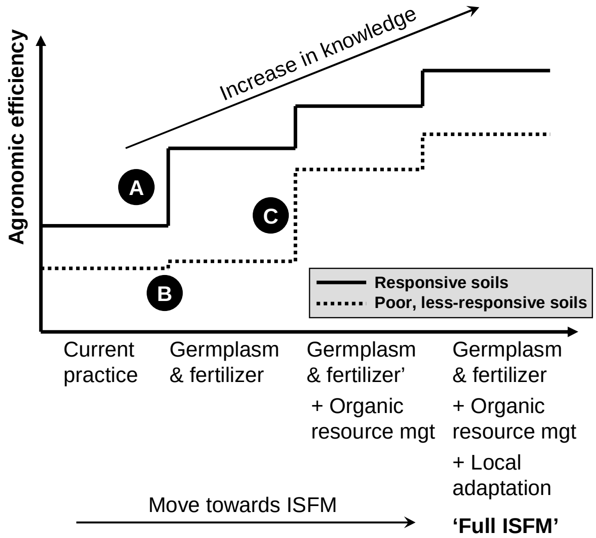
Figure 9: Average maize grain yields under farmers' and researchers' management in 160 fields (60 households) located at different distances form the homesteads in western Kenya. Current maize yields were measured on fields that may have received or not manure and fertilisers. Experimental plots were conducted by researchers on the same fields, employing improved maize varieties and proper crop husbandry (e.g., early planting, weeding, etc.). Half of the experimental plots received NPK fertilisers. Researcher managed plots that did not receive fertilisers (control) yielded on average between 0.5 and 1 t ha^{-1} more than under farmers' management.



This yield gap (1) is due to agronomic management and largely attributable to labour shortages on-farm. Fertiliser response under researchers' management represents the yield gap 2. The sum of the yield gaps of type 1 and 2 represents the potential yield improvement that may be achieved through intensification.

Integrated soil fertility management (ISFM) is knowledge-intensive, rather site-specific, and its implementation cannot be promoted all-at-once (Figure 10). The gradual testing and integration of individual technologies, in combination with increasing knowledge built in the communities and the necessary adaptations to the local conditions appears as the most sensible approach for the dissemination of ISFM. This research project aims at contributing to this process through the testing and adaptation of ISFM technologies in space and time, with the aid of field experimentation and scenario analysis through modelling.

Figure 10: Steps towards the implementation of integrated soil fertility management (ISFM). Quick steps in terms of increasing agronomic efficiency can be achieved on responsive soils (A). Poor responses to input-based technologies may be expected on less responsive soils (B) which may need proper organic matter management before they can respond to inputs (C). Full adoption of ISFM can only be achieved through local adaptation and capacity building (Adapted from: Vanlauwe et al, 2002).



Current research in cotton-based cropping systems of Togo (Kintche, Guibert, Cretenet & Tittonell, unpubl.) and in northern Zimbabwe (Baudron, Corbeels, Tittonell & Giller, unpubl.), and in different cassava production basins of sub-Saharan Africa (de Vries, van Wijk, Tittonell & Giller, unpubl.) aims at testing in space and time, and on farmers' conditions, different management alternatives to improve resource use efficiency that include combinations of organic and mineral fertilisers, legume-cereal rotations and intercropping (spatio-temporal diversification). To further illustrate the type of questions that will be covered in this research area, Box 1 presents an example of research that is taking place for the design of innovative sugar cane cropping systems in La Reunion, aimed at meeting the demands from different sectors of society with a more ecologically efficient agricultural production.

Box I - Ecological intensification of sugar cane: An example of research on a new cropping system

Sugar cane production is the main agricultural activity on the island of La Reunion, taking place on different agroecological zones (form 0 to 800 masl) and soil types, rainfed or under irrigation. Sugar productivity relies heavily on the use of external inputs, particularly mineral fertilisers used in large amounts. On the other hand, intensive livestock production on the island (dairy, pork, beef, poultry) is sustained on feeds that are mostly imported from abroad, generating nutrient surplus in manures and slurry that must be disposed safely. The disposal of such surpluses, as those from the sugar industry, poses a serious problem on the island. A closer integration of both industries, particularly through transfer of animal manures to fertilise cane, has been proposed. The demand for slurry to fertiliser sugar cane increased last year (2008) due to the increase in price of mineral fertilisers. A new law has been passed that prevents new pork production enterprises from establishing without an adjacent area of crops that can absorb the slurry produced. Longer-term alternatives, however, should contemplate a more integrated type of production system through promoting mix farming (i.e., in situ integration); although this is yet far from being locally acceptable and/or feasible, it is necessary to anticipate such trends and start researching alternative production systems. A step towards integration is the design of multi-functional sugar cane cropping systems able to provide also quality fodder for livestock. Evidence of the existence of market for fodder is the current commercialisation of sugar cane stover to feed livestock.

Alternatives are being proposed/ tested for the ecological intensification of sugar cane cropping systems in La Reunion, particularly among farmers of small scale, based on experiences from sugar cane agroecosystems around the world (Cuba, Australia, Mauritius). An alternative cropping system (prototype) is proposed that relies, among others, on the following technical measures:

1. Changing the plantation frame from the current uniform inter-row spacing of 1.5 m to planting in dual rows at 0.5 m, with inter-row distances of 1.3-1.4 m (RJ: 'ranges jumeles');
2. Introducing legumes in the system, as cover crops in between sugar cane cropping seasons, and as intercrops in between sugar cane rows (under RJ);
3. Using disposals from the animal industry to replace mineral fertilisers;
4. Using sub-products from the sugar industry to replace mineral fertilisers and soil pH correctors.

A number of advantages are expected/ hypothesised for this new cropping system:
(i) Less soil disturbance, since tillage is done only on the dual row space (a band of c. 0.7 m) while the wheels of the machinery run on the inter-rows that remain permanently covered with mulch;
(ii) Larger biomass production under RJ, with larger C inputs to the soil and potentially less organic matter decomposition in the no-tilled inter-row (C sequestration);
(iii) Earlier soil cover in the season that may contribute to out-compete weeds and to a more efficient use of rain and/or irrigation water;
(iv) Improved capture of applied/ available nutrients by sugar cane with a more homogeneous rooting pattern under RJ;
(v) Possibility to grow a short-cycled legume crop in the inter-rows that may be incorporated in the soil as green manure before the cane canopy closes;
(vi) N fixation by the legume cover crop, depending on the species used and their performance during the 'dry' period (improvable through irrigation?);
(vii) Capture of nutrients becoming available from the decomposition of the sugar cane residues during the fallow period by the cover crop;
(viii) The points above would also imply increased fertiliser use efficiency at system level and if this is coupled with use of organic nutrient sources, the use of mineral fertilisers on sugar cane can be reduced substantially;
(ix) Quality fodder production by introduction of a legume cover crop of nutritional interest, or by intercropping a legume to improve hay quality by collecting legume biomass and sugar can stover simultaneously;
(x) Better opportunities for crop-livestock integration, by making use of livestock disposals and providing locally-produced fodder (reducing import needs);
(xi) Diversification of production (i.e., the legume used as cover crop may be a grain legume such as soybean);

Although each of the technical measures to be implemented (1 to 4) presents operational questions (e.g., which legume species and varieties to use as cover crops, as intercrops, or what are the fertiliser equivalents of the sub-products of the sugar and animal industries, how much can be applied safely, etc.) that require specific research, they are tackled regarding the system holistically. Current research at La Reunion (Andrianteranagna, Marion, Letourmy & Tittonell, unpubl.) is evaluating the impact of the RJ system on biomass production (light use efficiency) and root development (water and nutrient use efficiency), and monitoring water and carbon balances in the traditional and the RJ systems. Screening trials of candidate legume species such as soybean, lablab, alfalfa, desmodium, mung bean, cowpea are being conducted in five agroecological zones in the island (Chaballier, Marion, Letourmy & Tittonell, unpubl.) to assess their biomass production performance and N fixation potential to be selected as cover crops in between sugar cane seasons. These lines of research represent first 'steps' to be integrated in the development of an innovative cropping system.

3.3 Sustainability and ecological services of agroecosystems (Area III)

This research area will tackle the following generic objectives:
(i) To contribute to the design and evaluation of sustainable and multi-functional agroecosystems, able to perform their expected service functions
(ii) To assess the long-tem stability (cf. Fig. 1) of multifunctional agro-ecosystems in face of increasing demographic pressure
(iii) To assess the long-tem reliability (cf. Fig. 1) of multifunctional agro-ecosystems in face of volatile international markets for raw materials
(iv) To study the (ecological and agronomic) determinants, processes and dynamics of the provision of environmental agroecosystem services (e.g., C sequestration, biodiversity conservation, agro-ecological services)
(v) To contribute to the design of strategies to rehabilitate the productivity and ecological functioning of degraded land

The provision of agroecosystem functions is regulated by their intrinsic properties, which functionality can be influenced by design. This research area aims at understanding and quantifying the effect of different agronomic and ecological determinants of such functions. The design of multi-functional agroecosystem poses research challenges at different scales and a need for their integration. On the other hand, current trends in world markets impose new demands on agricultural systems that may threaten their sustainability (e.g. the effect of fast growing Asian economies, high prices for foods and agricultural inputs, the impact of the 'bio-fuel fever', etc.). Without contradicting the conventional definition of sustainability based on environmental, social and economic aspects, this research proposal defines sustainable agroecosystems as those that fulfil acceptable levels of different indicators pertaining to their various properties (e.g., efficiency, diversity, stability, reliability, resilience – cf. section 2.1).

Soil organic carbon (C) is often proposed as an integrative indicator of soil health and performance, and thus often used to monitor long-term agroecosystem sustainability (e.g., Lal, 1997, Bouma, 2002). Land that is put under cultivation without C or nutrient inputs, as is often the case in smallholder farming systems, looses its original soil C stocks rapidly, depending on the capacity of the soils to store C (texture) and on the intensity of cropping (e.g. one versus two cropping seasons per year, type of tillage, erosion) (Figure 11). Current research in agroecosystems of East Africa (Henry, Tittonell, Vanlauwe, unpubl.) is assessing C stocks in different agricultural landscapes, and its vertical stratification down to soil depths of 1 m, to assess the capacity of smallholder systems to provide C storage services. This adds to the earlier assessment of above-ground C storage and biodiversity on the same type of landscapes (Henry et al., 2009).

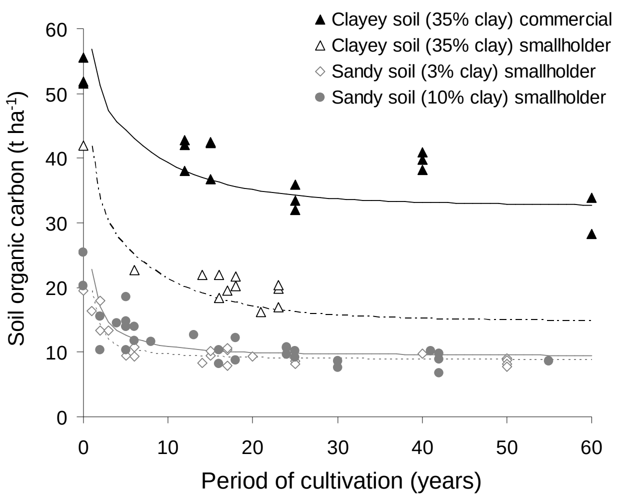


Figure 11: Chronosequences of soil carbon after forest clearance in soils of different texture and under commercial and smallholder farming. On sandy soils, a low 'apparent equilibrium' is reached within ten years of cultivation without inputs (smallholder). On clay soils, relatively large C stocks can be maintained when inputs are used (commercial). Further details in Zingore et al. (2005) and in Tittonell et al. (2007a).

In many smallholder farming systems, where crop residues are removed from the fields after harvest to be used as feeds for livestock, fuel or construction material, the main input of C to the soil is root biomass. Activities are envisaged, using the method of root assessment proposed by Chopart et al. (2009), to quantify the contribution of root C to the soils under different cropping systems (e.g., see Box I for the case of sugar cane cropping systems). Experimental trials to evaluate the effect of additions of organic matter of different quality on aggregate formation and soil C pools are being maintained already for five years in Ghana, Kenya and Zimbabwe and used to calibrate soil C models (Vanlauwe, Six, Mapfumo, Yeboah, Mugendi, Tittonell & Corbeels, unpubl.). Although the basic biophysical processes that govern C fixation and mineralisation operate at the scale of the cropping system or lower, the magnitude and the capacity of the agroecosystem to store C is highly influenced by processes operating at larger scales. Box II describes preliminary ideas extracted form a PhD research proposal that is currently being developed, aiming at analysing the feasibility of African agroecosystems to provide C sequestration services.

Box II. C sequestration in African soils requires a multi-functional agroecosystem approach

There are a number of factors limiting C sequestration in African soils, particularly in highly populated areas where smallholder subsistence farming predominates. A major biophysical limitation is poor soil fertility, which limits plant growth and therefore also the flow of C from the atmosphere to the biomass component of the agro-ecosystem. Many of these systems are N and P limited. Competing uses for crop residues on farmlands, to feed livestock, as fuel or for roofing, further limit the flow of C that has been fixed in crop biomass into the soil component. In many areas of Africa soil erosion accounts for large losses of C already stored in soils. Management of animal manure and composting has important implications for gas emissions, affecting the C balance at farm scale, as much as the burning of bio-fuels for cooking or heating. Use of green manures and leguminous agroforesty trees may have impact on N_2O emissions, also affecting the C sequestration balance.

A *strategic* question to be addressed is: What is the impact of major socio-ecological drivers and interactions that should be considered when designing interventions (policies, management plans, technologies) to address C sequestration in these complex agroecosystems? From this, a set of more *tactical* research questions can be derived, for example:

1. What is the magnitude of the impact of current demographic dynamics on the width of options for natural resource management strategies to promote C sequestration?
2. What are the major factors that determine appropriate natural resource management options for farmers who differ in access to monetary and natural resources within a certain location?
3. How do they vary across agroecological zones, along gradients of soil types and/or under different climatic scenarios?
4. How do they vary according to distance to, and development of, factor and output markets? And how under different global market scenarios?
5. How can different approaches to soil management be best integrated across heterogeneous farms to propend to effective C sequestration?
6. What is the role of social networks and other community-scale processes that regulate access to and management of natural resources in the design of strategies for C sequestration?
7. Which are the proper indicators to evaluate natural resource management strategies, considering varying spatio-temporal scales and embracing farmers' perspectives?

The ordering of these illustrative questions does not necessarily indicate their order of importance, nor their sequencing in time. Questions of a more *operational* nature will surely arise during the development and application of the necessary analytical tools. For example, questions around the theoretical aspects of representation and simulation of complexity applied to C and N dynamics at the village territory/ landscape/ regional levels. How can complex systems be best represented while simplified for their analysis?

Inputs of nutrient elements sufficient to substantially increase biomass production and thereby soil organic matter formation are unlikely to be justified by immediate returns. This reinforces the multi-functional character of agroecosystems: to improve C fixation and storage in the system it is first necessary to ensure that its basic functions of food and income generation are guaranteed. It is therefore important to understand how the strategic goal of improving the impoverished parts of a farm can be achieved within a framework of nutrient allocation decisions made to achieve tactical goals (tradeoffs between short and long term effects, e.g. resource degradation vs. food production). Considering (i) farmers' perceptions, goals and aspirations, (ii) short- and long-term impacts of management of natural resources and (iii) farm characteristics (diversity and heterogeneity) will allow deeper understanding of the system that is necessary to explore, evaluate and select options for desired natural resource management practices to ensure their uptake and implementation by rural communities.

Current research on the long term evolution of soil C in West African cropping systems, in contrasting agroecological zones of Mali (Cretenet, Tittonell, Corbeels, unpubl.), Benin and Cote d'Ivoire (Tittonell, Guibert, Cretenet, unpubl.) is studying the balance between agroecosystem primary productivity and organic matter decomposition, both determinants of soil C contents, by revisiting existing long-term experimental datasets (up to 40 years) on organic and mineral fertiliser use and crop residue management. This information is being analysed with the aid of process-based simulation modelling, to contribute also to our understanding of the hysteresis of African soils, which is proposed as a measure of their capacity to respond to restorative measures (Tittonell et al., 2008c). On-going research in the Zambezi valley of Zimbabwe (Baudron, Corbeels, Tittonell, unpubl.) aims at establishing chronosequences of soil C (cf. Figure 11) and plant biodiversity as a function of the average duration of fallow periods in land that has been cleared for the cultivation of cotton.

3.4 Tradeoffs, opportunities and conflicts in natural resource management systems (Area IV)

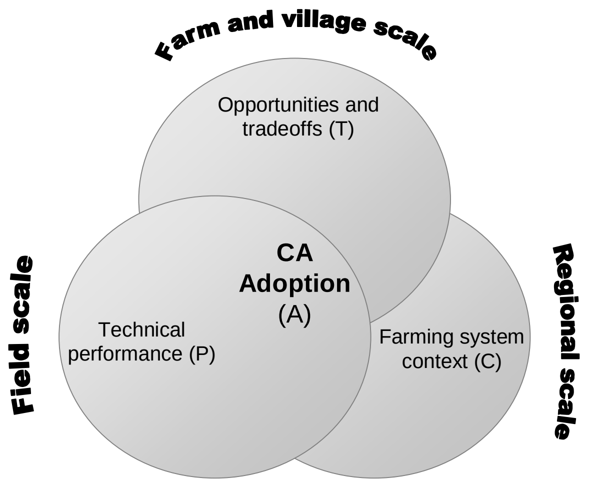
This research area will tackle the following generic objectives:
(i) To develop methodological approaches for the explicit analysis of tradeoffs between competing objectives in natural resource management, with emphasis on agriculture as a major form of natural resource use
(ii) To develop methodological approaches that account for the influence of the socio-cultural dimension of the agroecosystem in the design and implementation of innovative agricultural and natural resource management
(iii) To assess the impact of agricultural and other rural livelihood activities on ecological processes of the agroecosystem and surrounding natural ecosystems, which often represent the core of local human-nature conflicts
(iv) To contribute to the design of agroecosystems that allow a balanced achievement of local livelihood and nature conservation objectives

The smallholder farms that integrate most tropical agroecosystems are in general highly diverse, heterogeneous and dynamic, and therefore a single recommendation, management plan or policy will not suit all of them. These characteristics of smallholder systems should be considered in the design of interventions to address improved natural resource management. Farmers face tradeoffs in deciding on the management of their natural resource base, both at individual farm (e.g., choice of production activities, management of soil fertility, weeds, pest and diseases, tillage, livestock feeding, manure handling) and community scales (e.g., shared management of communal grasslands and woodlands, involvement in social networks). When resources become too scarce and/ or degraded, as is often the case in areas of dense human population, agriculture and resource 'harvesting' tend to expand onto adjacent natural ecosystems, obviously conflicting with nature conservation (e.g. Thornton et al., 2007).

This research area aims at integrating qualitative and quantitative research tools, marrying the type of information that originates from interactions with local communities with the more rigorous data collected through measurements, experimentation, and biophysical modelling. This integration will be done with models at different scales. Such a methodology should also allow analysing the potential niche for technology adoption by rural communities, as exemplified for the adoption of conservation agriculture technologies in Figure 12. Similarly, the integrated management of soil fertility, to be truly integrated, must go beyond the combination of germplasm, organic and inorganic fertilisers (cf. Figure 10) to tackle ways of improving nutrient cycling within the agroecosystem.

In many cases, the flows of nutrients within the agroecosystem are mediated by local rules and traditions in terms of access to communally shared resources (e.g., grazing and irrigation water rights, grazing of crop residues during the dry season, wood and surface soil extraction form woodlands, etc.). An example of research proposed to tackle the impact of community negotiations on biomass and nutrient transfers in African farming systems is described in Box III. A recent study by Rufino et al. (2009b) highlighted the importance of considering the collective management of resources used as livestock feeds to target the improvement of soil productivity at village scale. The approach combined intensive data collection on grazing rules and spatial patterns with modelling of communal decisions scenarios considering different farm types, and C and nutrient transfers within the community, combining soil-crop, grassland, livestock and manure storage models (Figure 13).

Figure 12: The determinants of adoption of conservation agriculture (CA) in African farming systems. Adoption (A) is conditioned by its technical performance (P), subject to the opportunities and tradeoffs (T) that operate at farm and village scales and constrained by different aspects of the context (C) in which the farming system operates, including market and socio-economic scenarios, cultural aspects defining the innovation system and the variability inherent to the physical environment (e.g. climate change). These groups of determinants show additive effects in conditioning the adoption of CA plus several interactions across scales (e.g., the performance of CA at field plot scale on a certain soil type may be conditioned by the amount of crop residues that can be kept as mulch; but these residues may be the only source of fodder for the village herd during the dry season) (source: CA2AFRICA project proposal, 2009).



Adoption = Performance + Tradeoffs + Context + (P x T x C)$_{interactions}$

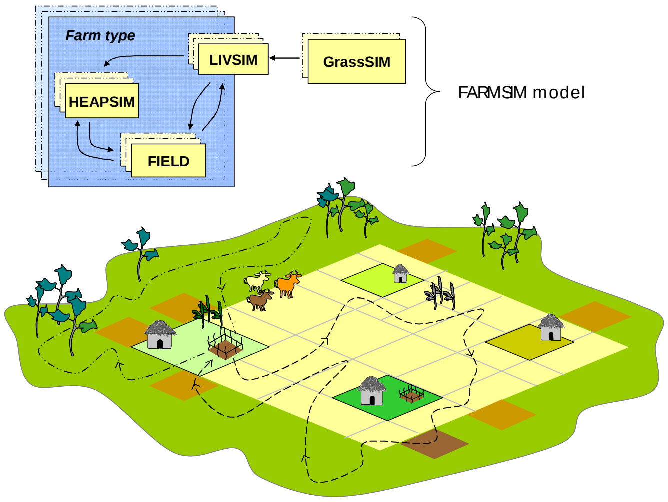


Figure 13: Representation of the modelling framework used to analyse resource interactions at village scale in a communal area of NE Zimbabwe. A simplified 'virtual' village was built based on the farm typology by Zingore et al. (2007), which distinguishes four farmer resource groups. Demographic pressure and competition for natural resources in these systems means that croplands must produce both food and feeds. Because of the continuous cultivation of the land, the removal of nutrients from the soils needs to be compensated by adding nutrient inputs and making efficient use of organic resources (crop residues and manure). The study analysed the dynamics of crop-livestock interactions under climate variability to identify opportunities for intensification. The models that were used simulated crop production at plot scale, grass production at grazing unit scale, animal production at individual level. Management decisions (feeding strategies, herding and cropping patterns, manure management) were implemented through rules derived from participatory work in the village. The most important transfers of nutrients: from grasslands to cropland, and between different farms were kept track of by integrating the different scales: individual animals, field, farm, grazing units, and village. Climate variability was accounted through simulating scenarios with different weather datasets collected locally, considering periods of 10 years. Source: Rufino et al. (2009b).

The degree of tradeoffs between objectives is often analysed (e.g., mapped – cf. Figure 5) using multiple goal optimisation models, often referred to nowadays as bio-economic models[10] (Janssen and van Ittersum, 2007). This approach has an economic bias and the limitation of being static (i.e., for a single season, or a single sequence of seasons) and thus not able to capture neither relevant biophysical feedbacks nor temporal variability in the system, particularly for long term analysis. An alternative

[10] These authors use the term bio-economic models rather restrictively to refer to multiple-goal linear programming models. This restricts bio-economic modeling to just static optimization models, in which biophysical processes are represented by fixed technical coefficients, without considering feedbacks in the system, and disregards bio-economic modeling using dynamic tools. For a more comprehensive review and categorization of bio-economic models see Brown (2000).

approach is using inverse modelling techniques (global search algorithms), which allows optimising a number of objectives by running dynamic models with a huge number of different combinations of parameters that represent management decisions (Tittonell et al., 2007b).

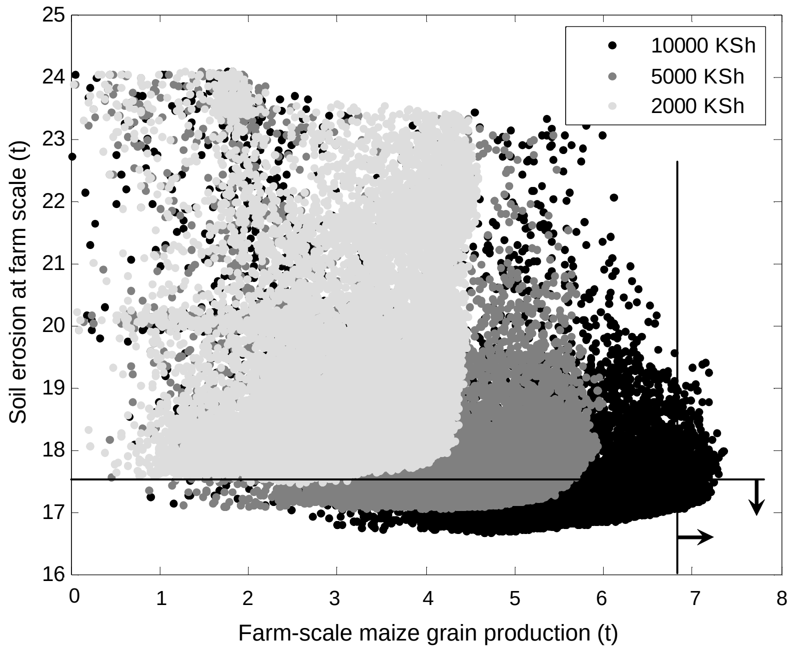


Figure 14: Results of the optimisation of the objectives 'maximising maize production at farm scale' and 'minimising soil losses by erosion at farm scale' for three scenarios of investment capacity (2000, 5000 and 10000 KSh ha-1 to invest in extra labour and agricultural inputs; 1 KSh = 0.75 US$) in a heterogeneous smallholder farm (2.2 ha) of Kakamega, western Kenya. The vertical and horizontal lines indicate, for the high investment scenario (10000 KSh ha-1), the subset of solutions that satisfy both objectives to the maximum. The simulations were done using the crop-soil dynamic model DYNBAL and the global search engine MOSCEM. The tradeoff curves between these objectives are represented by the outermost points (optimal solution sets) of the point clouds that satisfy both objectives. Source: Tittonell et al. (2007).

The design of intensive smallholder crop-livestock systems often leads to encountering tradeoffs between objectives. An example of research aiming at optimising crop-livestock interactions to promote the adoption of mulch-based cropping systems is the PhD thesis of S. Alvarez (2009) on the central plateau of Madagascar. On going research is also attempting to quantify and map the size of potential nutrient transfers from livestock to crops at sub-Saharan African scale, considering livestock populations of today and those projected for 2030 (van der Steen, Tittonell & Herrero unpubl.).

This research area will also include the analysis and design of alternative natural resource management systems in regions with marked conflict between human activities and nature conservation; examples of this are an approved PhD thesis for western Kenya (around Kakamega forest reserve), the on-going PhD thesis of S. Delmotte (rice production in La Camargue, France), and the PhD thesis proposal of A. Castellanos-Navarrete (forest encroachment and ecological knowledge in communities around the Lacandon forest, Chiapas, Mexico).

4. Agroecosystems, academy and partners

The agroecosystems to be targeted are principally small to medium scale, subsistence to semi-commercial crop-livestock systems in tropical environments. This will be facilitated through the articulation with the different research poles and partnerships of CIRAD in Africa, Latin America and Asia. Within the research unit Systèmes de Culture Annuels (SCA), to which the author is attached, research is going on through partnership in e.g. Cameroon, Benin, Togo, Mali, Burkina Faso, Kenya, Zimbabwe, Madagascar, Brazil, Paraguay, Vietnam and La Reunion.

Box III. Exemple de proposition de thèse

Analyse par modélisation des flux de biomasse et des transferts de fertilité à l'échelle du territoire villageois: opportunités pour une meilleure intégration agriculture – élevage

Résumé de la proposition:
En zone cotonnière d'Afrique de l'Ouest, du fait de la quasi disparition de la jachère causée par la pression démographique, la gestion des résidus constitue la principale source de maintien de la fertilité des sols dans un contexte d'augmentation du prix des intrants industriels. Les règles de vaine pâture appliquées dans cette zone, de même que les achats ou dons de fumure organique participent à des flux de biomasse se traduisant par un gradient de fertilité au sein du territoire. Parallèlement l'appropriation croissante de ces résidus (production de compost, stocks fourragers…) se traduit par une remise en cause de ces pratiques d'échange de biomasse végétale et des conflits croissants entre les différents types de producteurs (agriculteurs, agroéleveurs, éleveurs).
L'efficacité avec laquelle les ressources de l'exploitation sont mobilisées (eau, main d'œuvre, nutriments) dépend donc de flux pilotés à l'échelle du territoire. Améliorer la fertilité des sols dans les systèmes de production d'Afrique de l'ouest implique alors de raisonner à deux échelles: celle du territoire afin de raisonner les coordinations entre types de producteurs pour améliorer la fertilité du sol sur l'ensemble de l'espace, celle de l'exploitation afin de raisonner l'allocation des ressources productives pour améliorer la durabilité des systèmes de production.
En Afrique de l'Ouest, la gestion de la fertilité a souvent été abordée à l'échelle de la parcelle. Rares sont les approches qui tiennent compte de l'ensemble des ateliers de production gérés par le producteur à l'échelle de l'exploitation et encore moins de l'échelle du territoire. Des démarches d'élaboration de cadres de concertation entre les différents acteurs ruraux impliqués dans la gestion des ressources sont en cours d'élaboration au Mali ou au Burkina Faso (projet Fertipartenaires), mais ces démarches ne disposent pas d'outils de prospective leur permettant d'analyser les impacts sur leurs systèmes de production de scénarios d'intégration agriculture-élevage à l'échelle du territoire

L'objectif principal de cette étude est d'évaluer les impacts de différents scénarios d'intégration agriculture-élevage à l'échelle du territoire villageois sur la fertilité du sol et la durabilité des systèmes de production pour contribuer à l'élaboration de cadres de gestion des ressources agropastorales. Les **objectifs spécifiques** sont:

1. Caractériser la diversité des systèmes de production, leurs pratiques de gestion des ressources agro-pastorales et leurs impacts sur la base de ressources naturelles.
2. Analyser à l'aide de modèles à l'échelle de l'exploitation l'impact de l'allocation des ressources minérales et organiques sur la fertilité des terres et ses performances techniques et économiques.
3. Analyser à l'aide de modèles à l'échelle du territoire, les relations entre types d'acteurs (éleveurs transhumants et sédentaires, agriculteurs et agro-éleveurs), leurs mécanismes de coordination et leurs conséquences sur l'utilisation de la ressource biomasse.
4. Elaborer avec les acteurs de terrains des scénarios d'intégration agriculture-élevage à l'échelle de l'exploitation et du territoire et modéliser leurs impacts sur la productivité et la durabilité des systèmes de production

L'étude sera conduite dans 2 territoires villageois localisés en zone cotonnière du Burkina Faso et du Mali: Try au Mali; Koumbia au Burkina Faso zones pour lesquels on dispose d'analyses régionales (zonage, typologie d'UP, etc..). Les territoires dans chaque pays diffèrent par leur densité de population agricole et par la place et le type d'élevage qui y sont pratiqués. La démarche méthodologique comprend la construction d'une plateforme de simulation articulant modélisation des interactions et flux de biomasse à l'échelle du territoire et modélisation bioéconomique des exploitations. La plateforme sera validée en évaluant la capacité des diagnostics issus des simulations à servir de support pour des discussions avec les acteurs de terrains (producteurs, techniciens). Elles permettront de co-construire des scénarios innovants qui seront modélisés pour une évaluation ex-ante de leurs impacts sur la fertilité des sols et la productivité des systèmes de production.

Responsables d'encadrement : Marc Corbeels (CIRAD-Persyst, SCA), Nadine Andrieu (CIRAD-ES, Innovation), Pablo Tittonell (CIRAD-Persyst, SCA), entre autres.

The various research lines proposed in this project will be implemented through engagement with local and international partners from the spheres of research, extension and education. The participation of the author of this project in research and development consortia and his strong links with academic institutions in Africa, Europe and America provide the necessary network to participate in different international projects and in the co-direction of postgraduate students. The author has fluid contact with the following academic institutions: University of Wageningen (The Netherlands), Montpellier SupAgro (France), Universite de Butare (Rwanda), Florence University (Italy), University of Edinburgh (Scotland), Universidad de Matanzas (Cuba), Universidad Autonoma Metropolitana (Mexico), Universidad Politecnica de Madrid (Spain), University of Zimbabwe (Harare), Kenyatta University (Kenya), Universidades Nacionales de Rio Cuarto y de Lomas de Zamora (Argentina), University of Florida (USA). The author collaborates in different projects with the following international organisations: IITA, CIAT (TSBF), CIMMYT, ACIAR, ICRISAT, ICRAF, CIP and ILRI.

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Van Ittersum, M.K., Rabbinge, R., van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. Agric. Syst. 58, 309-330.

Van Keulen, H., 1995. Sustainability and long-term dynamics of soil organic matter and nutrients under alternative management strategies. In: Bouma, J. et al. (Eds.), Ecoregional Approaches for Sustainable Land Use. Kluwer, The Netherlands, pp. 353-375.

Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (eds.), 2002. Integrated Plant Nutrient Management in Sub-Saharan Africa. From concepts to practice. CAB International, Wallingford, Oxon, UK, 352 p.

Vanlauwe, B., Tittonell, P., Mukalama, J. 2006. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Nutrient Cycling in Agroecosystems 76, 171-182.

Weinberg, G.M. 2002. An Introduction to General Systems Thinking. Dorset House Publishing, 304 p.

Zingore, S., Manyame, C., Nyamugafata, P., Giller, K.E., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. Eur. J. Soil. Sci. 57, 727 - 736.

IV. Curriculum Vitae

1. Données personnelles

Nom:	Pablo Adrián Tittonell
Date de naissance:	29 janvier 1971
Nationalité:	Argentin
Etat civil:	Marié, un enfant
Adresse prof. :	Avenue Agropolis - TA B-102/02, 34398 Montpellier Cedex 5, France.
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2. Diplômes

PhD Ecologie de la Production et la Conservation de Ressources	*C.T. de Wit Postgraduate School for Production Ecology and Resource Conservation* – Université de Wageningen. Obtenu avec mention *Suma Cum Laude* (2007)
MSc Ecologie de la Production Agricole	Université de Wageningen: *Programme Crop Science*. Obtenu avec mention *Cum Laude* (2003).
MSc Sciences du Sol	Université de Río Cuarto (UNRC), Cordoba, Argentine. Obtenu avec mention (2004)[11].
Ingénieur Agronome	Université Nationale de Lomas de Zamora (UNLZ), Buenos Aires, Argentine. (1997).
Technicien de Laboratoire	Ecole Nationale de Formation Technique Nro. 1, "Otto Krause", Buenos Aires (1989).

3. Expériences professionnelles

Chercheur (Cadre Scientifique)[12]	Unité de Recherche Systèmes de Culture Annuels, Centre de coopération International en Recherche Agronomique pour le Développement (CIRAD) (2008). Avenue Agropolis - TA B-102/02, 34398 Montpellier Cedex 5, France. Tél: +33 (0) 4 67 61 44 09
Chercheur (Post-Doctorat)	Plant Production Systems, Department of Plant Sciences, Wageningen University (2007-2008). P.O. Box 430, 6700AK Wageningen, Pays-Bas. Tel: +31 317 482057
Chercheur associé	Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) (2005-2007). United Nations Avenue, P.O. Box 30677, Gigiri, Nairobi, Kenya
Assistant chercheur, Chercheur et Chargé de cours	Department of Soil Science[13], Universidad Nacional de Lomas de Zamora (UNLZ) (1998 – 2004). Ruta Prov. No 4, Km 2 (1836) Llavallol, Buenos Aires, Argentine. Tel: +54(11) 42826263
Agronome: Expérimentation au champ ; qualité des traitements des semences; gestion du personnel	Sector Investigación de la Producción – Monsanto Argentina División Semillas (1999 – 2000). Ruta Nac n° 8 Km 216 – Pergamino – Buenos Aires, Argentine. Tel: +54 (02477) 439255/439275
Agronome: Contrôle qualité et traitement des semences; conseils agricoles aux fermiers contractualisés	Sector Materias Primas y Acopios Externos – Molinos Río de la Plata S.A (1997 – 1998). Deán Funes 90 - Avellaneda, Argentine. Tel: +54 (011) 4201 5004 / 9.
Technicien de laboratoire	Temperley German School (1994 – 1996), Temperley; Escuela de Enseñanza Media Nº 2 (1992-1993) - Buenos Aires, Argentine

[11] En reconnaissance des travaux réalisés en 2000 et publiés ultérieurement
[12] Animateur de l'équipe scientifique CESCA (Conception et Evaluation de Systèmes de Culture Annuels) depuis mai 2009
[13] En collaboration également avec le Département d'Horticulture en 2000 et 2001 en recherches et enseignement

4. Expériences en formation, enseignement et conseil

- Université de Lomas de Zamora, Argentine. Divers cours dans le programme : *Edafologia* (Sciences du Sol) et divers cours en Ecophysiologie des Plants Cultivées (e.g., relation sol-plante et fertilité) (2000-2004). Chargé de cours à partir de 2003.
- Université de Rosario, Argentine. Cours *Postgraduate*: *Participatory modelling! - Linking models, experiments and participatory research for designing sustainable agroecosystems* (Octobre 2004)
- FLACSO (Faculté latino-américaine de Sciences Sociales) – Buenos Aires/Santiago du Chili: Chargé de cours *postgraduate* sur *Mathematical and statistical tools for agroecosystem analysis in rural development* conçu pour les diplômés en sciences sociales travaillant dans le développement rural (courant 2004).
- CAXI Association Civile (ONG): Subsistance et stratégies d'organisation des petits exploitants et travailleurs ruraux dans les régions sèches d'Argentine de l'Ouest (Provinces de Mendoza et San Juan), 2004/6. Une application de recherche participative liée à l'analyse de scénarios utilisant des modèles de simulation. Consultant entre 2004-2005.
- Fondation Zadorra – Vitoria-Gasteiz, Pays Basque, Espagne. Consultant entre 2005-2007. Courses pour les techniciens agricoles sur l'animation de réunions des diverses parties intéressées (agriculteurs, consommateurs, élaborateurs de politiques et chercheurs) dans le cadre du projet Ekolur: vers une production alimentaire agro-écologique et durable (Novembre 2005, Mars 2007).
- Université de Wageningen, Pays-Bas. Divers cours dans le programme : *Quantitative Analysis of Cropping and Grassland Systems* (QUACGS), Plant Production Systems, entre 2005 et 2008.
- Université Nationale du Rwanda, Butare, Rwanda. Cours *postgraduate*: Systèmes Agroforestiers, dans un programme d'exchange soutenu par l'agence de coopération de développement néerlandaise (Janvier 2007).
- Université du Zimbambwe, Harare, Zimbabwe. Cours *postgraduate*: Analyse des systèmes agricoles et des moyens de subsistance ruraux: Vulnérabilité et adaptation. Financé par ASARECA/IDRC/WUR (Février 2008).
- Universidad Nacional de Río Cuarto, Córdoba, Argentina. Cours *postgraduate*: *Análisis y modelización de agro-ecosistemas*, programme de formation en Agro-ecosystemes (Octobre 2008).
- Université Nationale du Rwanda, Butare, Rwanda. Cours *postgraduate*: *Farming Systems Modelling and Tradeoffs Analysis*, within the CIALCA (Consortium pour l'amélioration des moyens d'existence basés sur l'agriculture en Afrique Centrale), financé par le Belgian Development Cooperation Agency (VLIR) (Novembre 2008).
- Ecole Nationale Supérieure d'Agriculture de Montpellier (SupAgro), France. Cours: Modélisation des systèmes complexes appliquée à la gestion des productions et des ressources naturelles. Master en Sciences et Technologies Agronomie et agroalimentaire (Janvier 2009).
- Ecole Nationale Supérieure d'Agriculture de Montpellier (SupAgro), France. Cours: Diversité des systèmes de culture dans le monde. Master en Sciences et Technologies Agronomie et agroalimentaire (Janvier 2009).
- Universidad Autonoma Metropolitana de Mexico (UAM), Mexique. Cours *postgraduate*: *El enfoque de sistemas para el análisis integrado y el diseño de agro-ecosistemas*, financé par le 'Programa de fortalecimiento institucional del Departamento de Producción Agrícola y Animal (DPAA)' (Mars 2009)
- Cours international: *Systems approaches in agriculture. Design and evaluation of sustainable intensive systems and modernization*, dans le cadre du symposium: *Extensionismo, transferencias de tecnologías, aspectos socioeconómicos y desarrollo agrario sostenible"* Ciudad de La Habana, Cuba (Mai 2009)
- Universidad de la Republica, Uruguay. Cours de postgraduation: *El enfoque de sistemas para el análisis integrado y el diseño de agro-ecosistemas*, dans le cadre du *First Latin American and European Congress on Co-innovation of Sustainable Rural Livelihood Systems*, Minas, Uruguay, Avril 2010.

5. Engagement associatif

- Membre de l'Association Internationale des Systèmes de Culture (*International Farming Systems Association*)
- Membre de l'Association Argentine des Sciences du Sol (*Asociación Argentina de la Ciencia del Suelo*).

6. Liste de publications

6.1 Articles publiés dans les revues à facteur d'impact:

6.1.1 Soumis récemment:

Ebanyat, P., de Ridder, N., Tittonell, P., Majaliwa-Mwanjalolo, G., Oort, P., Delve, R.J., Giller, K.E., 2009. Characterisation of between- and within-farm variability in soil fertility in a low input farming system in Eastern Uganda. Geoderma, submitted: 01/2009.

Zingore, S., Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2009. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Agronomy Journal, submitted: 02/2009.

6.1.2 Acceptés et en cours de publication

Rufino, M.C., Dury, J., Tittonell, P., van Wijk, M.T., Herrero, M., Zingore, S., Mapfumo, P., Giller, K.E., 2009. Collective management of feed resources at village scale and the productivity of different farm types in a smallholder community of North East Zimbabwe. Agricultural Systems, accepted (11/2009) under revision.

Misiko, M., Tittonell, P., Giller, K.E., Richards, P., 2009. Strengthening understanding of mineral fertilizer among smallholder farmers in western Kenya. Agriculture and Human Values, accepted (4/2009), awaiting proofs.

6.1.3 Publiés (disponibles électroniquement)

Tittonell, P., Muriuki, A.W., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2009. Categorising and describing the diversity of rural livelihoods and their influence on within-farm soil variability in agricultural systems of East Africa - A typology of smallholder farms. Agricultural Systems, doi:10.1016/j.agsy.2009.10.001.

Chikowo, R., Corbeels, M., Mapfumo, P, Tittonell, P., Vanlauwe, B., Giller, K.E., 2009. Nutrient capture efficiencies and crop responses to soil fertility management in sub-Saharan Africa. Nutrient Cycling in Agroecosystems, doi: 10.1007/s10705-009-9303-6.

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Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2009. FIELD - A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32, 10-21.

Rufino, M.C., Tittonell, P., Reidsma, P., Lopez-Ridaura, S., Hengsdijk, H., Giller, K.E., Verhagen, A., 2009. Characterisation of N flows and N cycling in smallholder crop-livestock systems in the highlands of East and southern Africa using network analysis. Nutrient Cycling in Agroecosystems 85 :169–186.

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Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from smallholder farmers in East Africa. Field Crops Research 112, 24-36.

Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N., Giller, K.E., 2009. Beyond resource constraints – exploring the physical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agricultural Systems 101, 1- 19.

Henry, M., Tittonell, P., Manlay, R., Bernoux, M., Albrecht, A., Vanlauwe, B., 2009 Biodiversity, C stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agriculture, Ecosystems and Environment 129, 238–252.

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008. Yield gaps, nutrient use efficiencies and responses to fertilisers by maize across heterogeneous smallholder farms in western Kenya. Plant and Soil 313, 19–37.

Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2008. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya – explorations using the crop-soil model FIELD. Agronomy Journal 100, 1511-1526.

Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A., Giller, K.E., 2008. Using the crop simulation model APSIM to generate functional relationships for analysis of resource use in African smallholder systems: aggregating field-scale knowledge for farm-scale models. Agricultural Systems 97, 151–166.

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Tittonell, P., M.T. van Wijk, M.C. Rufino, J.A. Vrugt, K.E. Giller, 2007. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: a case-study from Kakamega district, western Kenya. Agricultural Systems 95, 76–95.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agricultural Systems 94, 376-390

Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M., Giller, K.E., 2007. Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research, 100, 348 – 368.

Tittonell, P., De Grazia, J., de Hek, S., Bricchi, E., 2006. Exploring land use scenarios by long-term simulation of soil organic matter in central Argentina. Spanish Journal of Agricultural Research 4, 381-389.

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Moccia, S., Chiesa, A., Oberti, A., Tittonell, P., 2006. Yield and quality of sequentially grown cherry tomato and lettuce under long-term conventional, low-input and organic soil management systems. European Journal of Horticultural Science 71, 183-191.

Tittonell, P., De Grazia, J., de Hek, S., Bricchi, E., 2006. Monitoring and predicting restoration of quality attributes of degraded land using an organic matter simulation model. Agricultura Tropica et Subtropica 39, 123-127.

Tittonell, P., Leffelaar, P.A., Vanlauwe, B., van Wijk, M.T., Giller, K.E., 2006. Exploring diversity of crop and soil management within smallholder African farms: a dynamic model for simulation of N balances and use efficiencies at field scale. Agricultural Systems 91, 71 – 101.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment 110, 149-165.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment 110, 166-184.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Giller, K.E., 2005. Estimating yields of tropical maize genotypes from non-destructive, on-farm plant morphological measurements. Agriculture, Ecosystems and Environment 105, 213-220.

Tittonell, P., De Grazia, J., Chiesa, A., 2005. Understanding functional relationships affecting growth and quality of field grown leaf lettuce in the green belt of Buenos Aires, Argentina. Acta Horticulturae 674, 367 - 373.

De Grazia, J., Tittonell, P., Chiesa, A., 2004. Growth and quality of sweet pepper (*Capsicum annuum* L.) transplants as affected by substrate properties and irrigation frequency. Advances in Horticultural Science 18, 181 – 187.

Tittonell, P., De Grazia, J., Chiesa, A., 2004. Emergencia y tasa de crecimiento inicial en plantines de pimiento cultivados en sustratos adicionados con polímeros superabsorbentes. Revista Ceres (Brasil) 50, 659 - 668.

De Grazia, J., Tittonell, P., Perinola, O.S., Caruso, A., Chiesa, A., 2003. Precocidad y rendimiento en zapallito redondo de tronco (*Cucurbita maxima* var. *zapallito* (Carr.) Millán) en función de la relación nitrógeno:potasio. Agricultura Técnica (Chile) 63, 428-435.

Tittonell, P., De Grazia, J., Chiesa, A, 2003. Nitrate and dry matter content in a leafy lettuce (*Lactuca sativa* L.) cultivar as affected by N fertilization and plant population. Agricultura Tropica et Subtropica 36: 82 - 87.

De Grazia, J., Tittonell, P., Germinara, D., Chiesa, A., 2003. Phosphorus and nitrogen fertilisation in sweet corn (*Zea mays* L. var. *saccharata* Bailey). Spanish Journal of Agricultural Research 1, 103-107.

De Grazia, J., Tittonell, P., Chiesa, A., 2002. Pepper (*Capsicum annuum* L.) transplant growth as affected by growing medium compression and cell size. Agronomie 22: 503 - 509.

Tittonell, P., De Grazia, J., Chiesa, A., 2002. Adición de polímeros superabsorbentes en el medio de crecimiento para la producción de plantines de pimiento (*Capsicum annuum* L.). Horticultura Brasileira 20, 641-645.

De Grazia, J., Tittonell, P., Chiesa, A., 2001. Efecto de la época de siembra, radiación y nutrición nitrogenada sobre el patrón de crecimiento y el rendimiento del cultivo de lechuga (*Lactuca sativa* L.). Investigación Agraria (España): Producción y Protección Vegetal 16, 355-365.

Tittonell, P., De Grazia, J., Chiesa, A., 2001. Effect of nitrogen fertilization and plant population during growth on lettuce (*Lactuca sativa* L.) postharvest quality. Acta Horticulturae 553, 67-68.

Tittonell, P., De Grazia, J., Chiesa, A., 2000. Adición de polímeros superabsorbentes a los sustratos en la producción de plantines de pimiento (*Capsicum annum* L.). Horticultura Argentina (ISSN 0326 4394) 19, 104-109.

De Grazia, J.; P.A. Tittonell; A. Chiesa. 2000. Influencia de la radiación y la nutrición nitrogenada sobre el patrón de crecimiento y el rendimiento en el cultivo de lechuga (*Lactuca sativa* L.). Horticultura Argentina (ISSN 0326 4394) 19, 29-33.

6.2 Chapitres d'ouvrages, rapports et articles de dissémination

Funes-Monzote, F., López-Ridaura, S., Tittonell, P., 2009. Designing ecologically intensive agricultural systems for Cuba. LEISA Magazine 25(1), 45-48.

Tittonell, P., Vanlauwe, B., Misiko, M., Giller, K.E., 2009. Targeting resources within diverse, heterogeneous and dynamic farming systems: towards an 'uniquely African green revolution'. *In*: A. Bationo, B. Waswa, J. Kihara, J. Kimetu (eds.) Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts, Springer, book in prep.

Misiko, M., Tittonell, P., 2009. Counting eggs? Smallholder experiments and try-outs as success indicators of adoption of soil fertility technologies. *In*: A. Bationo, B. Waswa, J. Kihara, J. Kimetu (eds.) Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts, Springer, book in prep.

Tittonell, P., Misiko, M., Ekise, I., 2008. Talking soil science with farmers. LEISA Magazine 24(2), 9 – 11.

Tittonell, P., Misiko, M., Ekise, I., 2008. Nutriments et fertilité au menu paysan! AGRIDAPE 24(2), 12 – 14.

Tittonell, P., Misiko, M., Ekise, I., 2008. Falando de ciencia do solo com os agricultores. Agriculturas 5(3), 35 – 38.

Vanlauwe, B., Tittonell, P., Mukalama, J. 2007. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Pp. 121-132 in: A. Bationo, B. Waswa, J. Kihara, J. Kimetu (eds.) Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities, Springer, ISBN 1402057598.

Tittonell, 2007. *Msimu wa Kupanda.* Targeting resources within diverse, heterogeneous and dynamic farming systems of East Africa. Dissertation, ISBN: 978-90-8504-807-7, 233 pp.

Giller, K.E., Misiko, M., Tittonell, P., 2006. Managing organic resources for soil amendment. LEISA Magazine 22(4), 16-17.

Tittonell, P., Misiko, M., Ekise, I., Vanlauwe, B., 2005. Feeding back the result of soil research: the origin, magnitude and importance of farmer-induced soil fertility gradients in smallholder farm systems. Report on discussion meetings at Emanyonyi Farmer Field School, Vihiga, western Kenya. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), Nairobi, Kenya, 23 pp.

Tittonell, P., 2003. Soil fertility gradients in smallholder farms of western Kenya. Their origin, magnitude and importance. Quantitative Approaches in Systems Analysis No. 25, ISBN 90-6754-713-1, Wageningen, The Netherlands, pp. 233.

Tittonell, P., 1992. Sokakullos de Oro – Recuperando un sistema de cultivo indígena en los Andes Bolivianos. Milenaria 4, 12 – 14.

6.3 Actes (des 3 dernières années)

Rufino, M.C., Tittonell, P., 2009. Translating farmers' objectives and preferences into scenario sets for the design and assessment of (smallholder) crop-livestock systems. II Biennial International Farming Systems Design 2009, Monterrey (CA), USA, 23-26 August.

Funes-Monzote, F., Tittonell, P., López-Ridaura, S., 2009. Diversidad y eficiencia – Elementos clave para una agricultura ecologica intensive. Oral presentation at the International Symposium Agrodesarrollo 2009, Varadero, Cuba, 25-28 May.

Tittonell, P. Guibert, H., Cretenet, M., 2009. Understanding the potential impact of climate change on long term soil carbon dynamics in tropical cropping systems - evidence from West Africa. European Geoscience Union General Assembly, Vienna, Austria, 19-24 April 2009.

Kintche, K., Guibert, H., Cretenet, M., Tittonell, P., 2009. Modelling the evolution of soil carbon stocks in cotton-based cropping systems of Togo. European Geoscience Union General Assembly, Vienna, Austria, 19-24 April 2009.

Rufino, M.C., Dury, J., Tittonell, P., van Wijk, M.T., Herrero, M., Zingore, S., Mapfumo, P., Giller, K.E., 2009. Competing use of organic resources, climate variability and village-scale interactions in a communal area of NE Zimbabwe. AgSAP Conference, 10-12 March, Egmond aan Zee, The Netherlands.

Tittonell, P., M.C. Rufino, M.T. van Wijk, M. Herrero, M. Corbeels, C. Pacini, J. Smith, S. Karanja, C. Quiroz, P. Mapfumo, J. K'ungu, F. Baijukya, C. Kaizzi, M. Mwale, O.M. Sanogo, E. Yeboah, D. Nwage, B. Vanlauwe, A. Albrecht, N. de Ridder and K.E. Giller, 2009. Integrated assessment of nutrient management options in smallholder farming systems – the NUANCES framework. AgSAP Conference, 10-12 March, Egmond aan Zee, The Netherlands.

Tittonell, P., M. Corbeels and K.E. Giller, 2009. The interaction between sub-optimally available resources for crop production as implemented in the simplified model FIELD. AgSAP Conference, 10-12 March, Egmond aan Zee, The Netherlands.

Adam M., Tittonell P., Bergez J.E., Ewert F., Leffelaar P., 2008. From detailed to summary models of the crop-soil system for larger scale applications. 10th Congress of the European Society for Agronomy (ESA), 15-19 September, Bologna, Italy.

De Grazia, J., Barrios, M.B., Tittonell, P., Rodríguez, H.A., Andrada, H.I., Fernández, F., 2008. Dinámica del agua en el suelo bajo diferentes sistemas de labranza en una rotación trigo-soja. Congreso Argentino de la Ciencia del Suelo, 13-16 May, San Luis, Argentina.

Figueroa, B.M, Tittonell, P., Ohiokpehai, O., Giller, K.E., 2008. The contribution of traditional vegetables to household food security in two communities of Vihiga and Migori Districts, Kenya. International Symposium: Underutilized plants for food, nutrition, income and sustainable development, 3-7 March, Arusha, Tanzania.

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