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Abstract:

We analyze trends in yield growth and yield variability of barley, maize, oats, rye triticale and wheat in Switzerland from 1961 to 2006. In contrast to linear trends in cereal yield growth that are usually assumed for Europe, cereal yields have leveled off due to widespread extensive cereal production in Switzerland since the early 1990's. This might also indicate prospects for future crop yield developments in other countries if similar farming practices are widely-used. Even though we find increasing yield variability for barley and rye, no increasing trend in relative yield variability (relative to yield levels) is found for all analyzed crops. Furthermore, this study emphasizes the importance of robust regression methods to ensure reliable results in trend estimation.

Keywords:

climate change, crop yield development, detrending, robust regression, Switzerland, crop yield variability, agri-environmental policy

1. Introduction

Crop yields increased remarkably worldwide in the last century due to technological development (Cassman et al., 2003, Hafner, 2003). This development was caused by the adoption of improved crop management practices, crop varieties and the improved adaptation to environmental conditions, the usage of fertilizers, herbicides, fungicides and insecticides as well as by the adoption of mechanization and irrigation (Calderini and Slafer, 1998, Egli, 2008, and Evans, 1997). Agricultural policy facilitated this trend by governmental investment in agricultural and research infrastructure and price support (Khush, 1999). Trends in crop yield growth are analyzed in order to predict future land use and food supply (e.g Ewert et al., 2005).

Hafner (2003) found a prevalence of linear growth, i.e. constant annual yield increase, on a global scale. Trends of slowing yield growth that are indicated for some countries are caused by economic and biophysical factors. Using the example of Swiss cereal yields, we show that agricultural policy can be a further reason for slowing yield growth. Switzerland introduced a direct payment scheme in 1992 that fostered extensive cereal farming and caused leveling-off of cereal yields since the early 1990s.

Besides analyzing trends of growth for Swiss cereal yields, this study aims to describe the development of yield variability for the period 1961-2006. Furthermore, we emphasize the importance of regression methods that are not affected by exceptional yield events. In this study we employ robust regression to estimate trends in yield growth, which ensures efficient and reliable results in yield trend estimation.

2. Material and Methods

Yield Trend Analysis

Annual yield data is fitted to two different models: a linear and a quadratic trend model. The linear trend model is defined as follows:

$$Y_{pti} = \alpha_0 + \alpha_1 \cdot t_i \qquad (1)$$

t_i is the time index with $t_i = 1$ in 1961 ($t_i = 1$ in 1985 for triticale), Y_{pti} is the predicted yield in t_i, α_0 is the model intercept and α_1 is the annual yield change. In this model, annual yield growth is assumed to be constant over time. Besides linear trends, leveling-off of yields might be evident. Such saturation type response is described by a quadratic model:

$$Y_{pti} = \beta_0 + \beta_1 \cdot t_i + \beta_2 \cdot t_i^2 \qquad (2)$$

t_i^2 is the squared time index, β_0 is the model intercept and β_1 the linear trend. Coefficient β_2 indicates, if negative, a slowing (or negative) trend of yield growth. Annual yield growth is assumed to be nonlinear in this model. The linear model is rejected in favor of the quadratic model if and only if the latter provides a better goodness of fit and β_2 is smaller than zero at a 0.05 level of significance. We are aware that other functional forms, such as higher degree polynomials or log-linear trend models, are also frequently applied to estimate crop yield development over time. For the sake of brevity in our analysis, we restrict numerical examples on linear and quadratic trend models.

Estimation Techniques

Two regression techniques are employed in this study to estimate the coefficients of the linear and the quadratic model: Ordinary Least Squares (OLS) regression and Re-weighted Least Squares (RLS) regression, a robust regression technique. OLS estimation is vulnerable to outliers, i.e. observations that deviate from the relationship described by the majority of the data (Hampel et al., 1986, and Rousseeuw and Leroy, 1987). They can have a large influence on estimation results. For time trend analysis, particularly outliers that occur at the end of time series have a large (leverage) effect on coefficient estimation. In OLS estimation, one outlier can be sufficient to move the coefficient estimates arbitrarily far away from the actual underlying values. Possible sources of outlying observations in the analysis of yield growth are methodological changes, inaccuracy in data collection and climatic extreme events such as droughts and heavy rainfalls (Calderini and Slafer, 1998). Moreover, wrong model assumptions can cause outliers. Outliers occur, for instance, if data that follows a nonlinear trend is fitted to a linear model.

In order to avoid vulnerability of regression analysis to outliers, the influence of these exceptional observations is usually reduced by using moving averages of yields for trend estimation (e.g. Calderini and Slafer, 1998, and Reilly et al., 2003). However, regression analysis with moving averages of yield observations does not allow for sufficient analysis of regression residuals, which describe yield variability, and reduces the degrees of freedom of the regression analysis.

In contrast, robust regression is used in this study. Robust regression techniques identify and delete (or down weight) outlying observations to isolate the true underlying relationship. Using farm level maize yield data from the US, several robust regression methods are employed to estimate linear trends by Swinton and King (1991). They conclude limited ability to detect outliers in yield data for some robust regression techniques. In particular, outliers that occur at the end of time series have a large effect on coefficient estimation and are not detected by several robust regression methods. They further conclude that if no outliers occur, robust regression methods perform inferior to OLS. However, an efficient and robust procedure, not taken into account by Swinton and King (1991), is the RLS regression proposed by Rousseeuw (1984). This regression technique is employed in our analysis and described in the following. The simple idea of RLS is to detect outliers in a first step and to estimate coefficient estimates using an outlier free dataset in a second step of analysis with least squares regression.

The Least Trimmed Squares (LTS) estimator is applied to identify outliers. This estimator can cope with outliers and particularly with outliers that have a leverage effect on the coefficient estimation. The basic idea of LTS estimation is to trim (i.e. not take into account) observations for the estimation of regression coefficients, which considerably deviate from the pattern described by the majority of the data. The LTS fitting criterion is defined as follows:

$$\underset{\hat{\beta}}{Min} \sum_{ti=1}^{h} (r^2)_{ti:n} \qquad (4)$$

$(r^2)_{(ti)}$ are the ascending ordered squared (robust) residuals and h is the so-called trimming constant. Following Rousseeuw and van Driessen (2000), we use $h = \left[(3n + p + 1)/4\right]$. The computation of LTS coefficients is neither explicit (such as for OLS) nor iterative but follows an algorithm that is described in Rousseeuw and Leroy (1987). Because the efficiency of LTS estimation is low, results allow not for trustful inference (Rousseeuw and Leroy, 1987). To provide robust and efficient coefficient estimates, LTS is only used as a data analytic tool that identifies outliers. An observation is indicated as an outlier if the absolute standardized LTS residual ($|r_{ti} / \hat{\sigma}|$) exceeds the cutoff value of 2.5, which is motivated by a (roughly) 99% tolerance interval for Gaussian distributed residuals (Sturm and de Haan, 2001). r_{ti} is the (robust) LTS regression residual and $\hat{\sigma}$ the (robust) LTS scale estimate.

RLS regression is a weighted least squares regression that gives zero weights to observations that are identified as outliers. This estimator is more efficient than the LTS estimator and much more robust than the OLS estimator. Thus, it combines robustness and efficiency properties of LTS and OLS estimation, respectively. Therefore, this regression technique is suitable to ensure efficient estimation in presence but also in absence of outliers (Rousseeuw and Leroy, 1987).

We are aware that also other regression methods, in particular the MM-estimator, have these robustness and efficiency properties. Based on a robust but inefficient regression procedure (such as LTS or S-estimation) as initial estimator, a redescending M-estimation is conducted that ensures high efficiency of the MM-estimator (see e.g. Yohai, 1987, for details). In contrast to RLS, only extreme outliers are deleted and moderate outliers are down-weighted in the final M-estimation step, which can be calculated by an iteratively re-weighted least squares approach. Because of this smallish difference in the weighting scheme, the coefficient estimates are not expected to differ substantially. However, confidence intervals of RLS estimation might be systematically shorter than those of MM-estimation because deletions of outliers are not taken into account for standard error calculation in RLS estimation. We particularly expect outliers to come from extreme climatic events but also from assuming the wrong underlying model and inaccuracy in data collection. Because errors in the model assumptions or data collection do not have to be reflected necessarily in the standard errors of the coefficient estimates and RLS allows for better interpretation of outliers from our point of view, we choose RLS instead of MM-estimation in our analysis[1].

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[1] However, we repeated all robust estimations in this study with MM-estimation based on S-estimation starting values and using Tukey's bisquare function. It shows that coefficient estimates of RLS and MM estimation are similar and that the levels of significance that are presented in this study based on RLS are in line with the results of the MM-estimation.

As we expect heteroscedastic residuals for the estimation of trend lines (see below), we re-examined significance levels of coefficient estimates if the White or the Breusch-Pagan test indicated heteroscedasticity in order to ensure correct regression inference. To this end we use a consistent estimate of the covariance matrix that follows White (1980) provided by the ACOV option in the REG procedure of the SAS statistical package (SAS Institute, 2004). The ROBUSTREG procedure of this program is used for RLS estimation.

Trends in Yield Variability

Because the assessment of yield variability based on non-detrended yield data would be biased upwards in the presence of a trend in crop yields, we use regression residuals to analyze the development of yield variability over time. Yield variability is defined as the absolute residual of the yield growth trend estimation, i.e. the absolute difference between observed and predicted yield: $|r_{ti}| = |Y_{ti} - Y_{pti}|$. Residuals are calculated based on the selected yield growth trend model (linear or quadratic). Increasing absolute residuals indicate increasing absolute yield variability, and vice versa. To this end, absolute RLS regression residuals are fitted to a linear model:

$$|r_{ti}| = \delta_0 + \delta_1 \cdot t_i \qquad (5)$$

If absolute yield variability increases, coefficient δ_1 is significantly larger than zero, and vice versa.

In addition, we analyze trends in relative yield variability. This measure of variation is closely related to the coefficient of variation and is more appropriate to analyze yield variability if yields increased enormously over time. Relative yield variability is defined as the ratio of the absolute regression residual and the predicted yield and is fitted to a linear trend model.

$$|r_{ti}| / Y_{pti} = \gamma_0 + \gamma_1 \cdot t_i \qquad (6)$$

Such as for absolute yield variability, a significant and positive estimate for γ_1 indicates increasing relative yield variability, and vice versa.

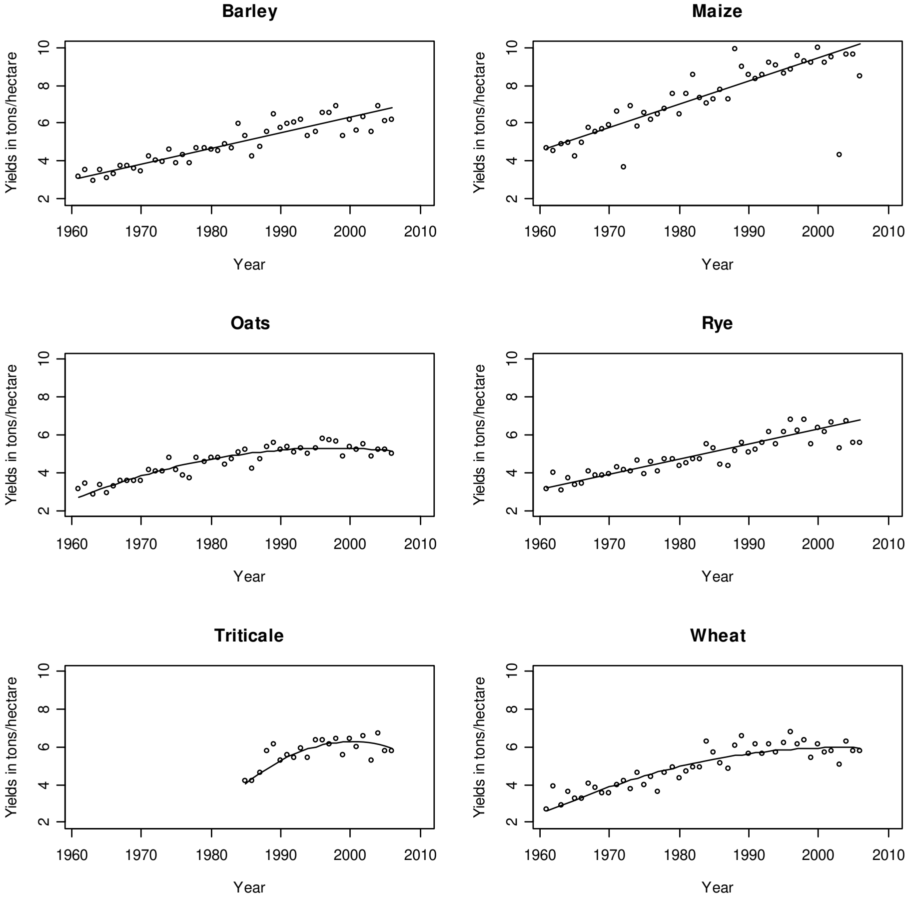
Data

Yield time series for barley (*Hordeum vulgare L.*), maize (*Zea Mays L.*), oats (*Avena L.*), rye (*Secale cereale L.*), triticale (*X Triticosecale*) and wheat (*Triticum L.*) for Switzerland are taken from the internet database of the Food and Agriculture Organization (FAO, 2008). FAO yield level data are derived by dividing the total national production quantity by the total area harvested. These time series cover the period of 1961 to 2006. Data for triticale is only available for 1985-2006. Data on the national level is applied because long term farm level data is not available, although we are aware that analysis of aggregated yield data is likely to under-estimate yield variability. Wheat, barley and maize are the most important cereals in Switzerland, covering about 54%, 22% and 12% of the total cereal production acreage in 2005 (SBV, 2006).

3 Results

Yield levels (in tons per hectare) for barley, maize, oats, rye, triticale and wheat in Switzerland from 1961 to 2006 and estimated trends are shown in Figure 1. It shows that yield levels increased by between 65% (oats) and 100% (maize) in the period studied if the median yields of the time periods from 1961 till 1965 and from 2002 till 2006 are compared.

Figure 1. Swiss cereal yields (1961-2006) and estimated trends.



Note: Barley, maize and rye are fitted to a linear model (equation 1). Oats, triticale and wheat are fitted to a quadratic model (equation 2). Data for triticale is available only for 1985-2006.
Source: FAO (2008).

Linear Model. Estimation results for the linear model for both OLS and RLS estimation are presented in Table 1. It shows positive and significant linear trends in yield growth for all crops. For RLS estimates, the annual crop yield increase ranges from 65 kg/ha (oats) to 124 kg/ha (maize). Because there are no outliers identified for triticale, both estimation techniques (OLS and RLS) coincide. Thus, coefficient estimates and standard errors for triticale are equal for both estimation techniques.

Table 1. OLS and RLS estimation results for the linear model (equation 1).

	N	Intercept	Linear Trend	Adj. R^2	Outliers
			OLS		
Barley	46	3.086	0.077	0.83	
Maize	46	4.704	0.110	0.66	
Oats	46	3.306	0.053	0.75	
Rye	46	3.274	0.069	0.81	
Triticale	22	4.956	0.066	0.34	
Wheat	46	3.233	0.072	0.76	
			RLS		
Barley	46	3.029	0.082	0.86	1999, 2003
Maize	46	4.514	0.124	0.94	1972, 1982, 1988, 2003, 2006
Oats	46	3.133	0.065	0.85	1999, 2003, 2004, 2005, 2006
Rye	46	3.140	0.078	0.87	2003, 2005, 2006
Triticale	22	4.956	0.066	0.34	---
Wheat	46	3.185	0.075	0.79	2003

Note: All coefficients are significant at the .01 level. For RLS, adj. R^2 follows from the weighted least squares estimation (equation 5). Data for triticale is available only for 1985-2006.

The year 2003 is identified as an outlier for all crops but triticale because the summer drought in 2003 caused low crop yields in throughout Europe (Ciais et al., 2005). As shown in Figure 1 for Switzerland, this summer drought led to smaller cereal yields than estimated by the trend lines. In particular the reduction of Swiss maize yields was large[2]. Maize had not terminated growth by the time of the heat wave. In contrast, other (in particular winter sown) cereals had terminated growth by time of the heat wave and were thus less affected by the 2003 summer drought (Ciais et al., 2005). Due to the vulnerability of OLS to extreme yield observations, such as the low yield levels in 2003, linear trend estimates for all crops but triticale are smaller for OLS than for RLS estimation as shown in Table 1. If the linear trend estimates identify groups of consecutive outliers such as for oats, this might indicate a wrong model specification. A quadratic model might be more appropriate instead.

Quadratic Model. Estimation results for the quadratic model for both OLS and RLS estimation are presented in Table 2. Results for three crops indicate significant trends of saturation for OLS estimation: maize, oats and wheat. However, the significance of this trend for maize is due to the exceptional small yield in 2003. Thus, this significant trend

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[2] The 2003 maize yield observation might be under-estimated in the FAO database, as the Swiss statistic (SBV, 2006) indicates a higher yield level. However, the exceptional low yield level is in line with observations for other European countries (FAO, 2008).

of saturation in maize yields disappears if RLS estimation is employed. For the RLS estimation, three crops show a significant trend of saturation: oats, triticale and wheat. Moreover, the goodness of fit is higher than in the linear RLS model for these crops (cp. Table 1). Therefore, we reject the linear in favor of the quadratic model for oats, triticale and wheat. The linear model is selected for barley, maize and rye.

Table 2. OLS and RLS estimation results for the quadratic model (equation 2).

	N	β_0	β_1	β_2	**Adj. R^2**	**Outliers**
				OLS		
Barley	46	2.810**	0.112**	-0.0007	0.84	
Maize	46	3.824**	0.219**	-0.0023*	0.70	
Oats	46	2.692**	0.130**	-0.0016**	0.85	
Rye	46	3.143**	0.086**	-0.0004	0.81	
Triticale	22	4.073**	0.287**	-0.0096	0.58	
Wheat	46	2.618**	0.149**	-0.0016**	0.81	
				RLS		
Barley	46	2.837**	0.106**	-0.0005	0.86	1999, 2003
Maize	46	4.311**	0.151**	-0.0006	0.94	1972, 1982, 1988, 2003, 2006
Oats	46	2.552**	0.148**	-0.0019**	0.89	1962, 1977, 1986
Rye	46	3.346**	0.051**	0.0006	0.88	2003, 2005, 2006
Triticale	22	3.744**	0.313**	-0.0097**	0.81	1988, 1989, 2003
Wheat	46	2.418**	0.165**	-0.0019**	0.83	1962

Note: For RLS, adj. R^2 follows from the weighted least squares estimation (equation 5). Data for triticale is available only for 1985-2006.
(*) Significant at the .05 level
(**) Significant at the .01 level

Even though coefficient estimates provided by OLS and RLS never significantly differ, the example of the differing regression inference for maize in the quadratic model shows the vulnerability of OLS estimation and respective regression inference to outliers that occur at the end of the time series and underlines thus the importance of appropriate regression methods to detect outliers. Correcting for the heteroscedastic error structure does not change the levels of significance of the coefficient estimates neither for the linear nor for the quadratic model for all crops.

Trends in yield variability. Absolute regression residuals are calculated from the selected trend model and are fitted to a linear model following equation (5). Therefore, increasing yield variation is indicated by a significant and positive trend, and vice versa. Increasing yield variation, i.e. less stable yield, is only indicated for barley and rye (Table 3). We find positive but not significant trends in yield variation for maize, triticale and wheat.

For oats the yield variation trend is, however, negative but not different from zero on a 0.05 level of significance.

Table 3. Trend estimation of yield variability.

Crop	N	Intercept	Trend	Adj. R^2
			Absolute residuals (equation 5)	
Barley	46	0.125	0.011**	0.22
Maize	46	0.196	0.015	0.03
Oats	46	0.268**	-0.001	-0.02
Rye	46	0.133	0.009**	0.16
Triticale	22	0.286	0.005	-0.04
Wheat	46	0.341**	0.001	-0.02
			Relative absolute residuals (equation 6)	
Barley	46	0.051**	0.001	0.04
Maize	46	0.056	0.001	-0.01
Oats	46	0.080**	-0.001*	0.06
Rye	46	0.055**	0.001	0.00
Triticale	22	0.062*	-0.000	-0.05
Wheat	46	0.106**	-0.001	0.02

(*) Significant at the .05 level
(**) Significant at the .01 level

Relative yield variability is analyzed to assess the trend of yield variability relative to the trend of yield growth (equation 6). Increasing yield variability can be offset by increasing yield levels in this concept. Table 3 shows negative and significant trend for relative yield variability for oats. Thus, oats yields became, relative to the trend of yield growth, more stable from 1961 to 2006. We find increasing, but not significant, trends in relative yield variability for barley, maize and rye. Moreover, negative but not significant trends are estimated for triticale and wheat.

4. Explaining slowing yield growth

The evidence for slowing yield growth of Swiss cereals that is given by our analysis is unexpected because annual yield increase is assumed to be stable since 1960 in the developed world in general (Cassman et al., 2003) and in Europe in particular (e.g. Ewert et al., 2005). This is also indicated by a comparison of the development of wheat and maize yields in France, Germany and Switzerland (Finger, 2008). The latter analysis shows that wheat yields developed similar until the early 1990's. Thenceforward, Swiss wheat yields leveled off and wheat yields in France and Germany increased further. Maize yields in these countries developed almost similar in the period from 1961 to 2006. Even though Calderini and Slafer (1998) indicated leveling-off of wheat yields in some European countries, Hafner (2003) showed, in a more recent analysis, that trends of slowing yield growth can be found only in countries that are characterized by small per-capita GDP and low latitude[3]. Because economic and biophysical reasons for slowing yield growth can be excluded for Switzerland, we think that a change in agricultural policy caused the observed leveling-off[4]. In 1992 ecological direct payments that foster extensive cereal farming have been introduced. In this ancillary payment scheme no application of fungicides, plant growth regulators, insecticides and chemical-synthetic stimulators of natural resistance is allowed (BLW, 2008)[5]. Rapeseeds and all cereals but maize are included in this ecological direct payment scheme, which reduced the harmful environmental impacts of the Swiss cereal production (BAFU, 2006). As a result, the share of extensive to total area under cereals (except maize) increased from 37% in 1992 to 54% in 1997 and remained stable at about 50% since then (BLW, 1993-2007). For breadstuff production, the share of area under extensive production increased from about 25% in 1992 to 45% in 1997 and remained stable at this level thenceforward (BLW, 1993-2007). This indicates a relatively stable share of extensive wheat production since the mid 1990's, because the acreage used for breadstuff production mainly consists of wheat (1996-2005 average: 94%, SBV 1997-2006) and the area under wheat is mainly used for breadstuff production (1996-2005 average: 99%, SBV 1997-2006). A crop specific analyses as well as detailed comparison of extensive and conventional farming practices are not possible due to a lack of data and require thus farm level data, which is beyond the scope of this study.

The identification of 1992 as a turning point is also supported by the crop yield data. The Chow-test identifies a structural break within the estimated linear trend lines for oats, rye, triticale and wheat assuming a 0.05 level of significance. This hypothesis is further

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[3] The only exception was Austrian maize, which indicated slowing yield growth (Hafner, 2003).

[4] The analysis of Hafner (2003) did not indicate slowing yield growth of Swiss wheat yields because of the shorter time series (1961-2001) that is taken into account compared to our analysis.

[5] These annual payments decreased from 800 CHF per hectare and year in 1992 to 400 CHF per hectare in 1999 and remained on this level thenceforward.

supported by separated estimations of trend lines for the periods 1961-1991 and 1992-2006 (Table 4).

Table 4 Linear trends in crop yield growth 1961-1991 and 1992-2006.

	1961-1991			**1992-2006**		
	Intercept	**Trend**	**Adj. R^2**	**Intercept**	**Trend**	**Adj. R^2**
Barley	2.946**	0.086**	0.88	5.904**	0.021	-0.04
Maize	4.443**	0.128**	0.88	8.721**	0.073**	0.49
Oats	2.934**	0.082**	0.87	5.386**	-0.016	-0.02
Rye	3.312**	0.064**	0.76	6.112**	-0.006	-0.07
Triticale †	(3.972**)	(0.284*)	(0.53)	5.893**	0.014	-0.06
Wheat	2.750**	0.102**	0.85	6.091**	-0.023	-0.01

Data for triticale is available only for 1985-2006. RLS is used for coefficient estimation. (†) Results for triticale from 1985-1991 are not considered due to the small number of observations in this time series.
(*) Significant at the .05 level
(**) Significant at the .01 level

For the period from 1961 to 1991 there is a significant positive trend of yield growth for all crops (Table 4). In contrast, for the period from 1992 to 2006 there is only a significant positive trend of yield growth for maize. For barley, oats, rye, triticale and wheat no significant trend is indicated. Thus, all cereals that are covered by the ecological direct payments for extensive farming show no trend of yield growth since the introduction of these direct payments in 1992. However, the annual maize yield increase for the period from 1992 to 2006 (73 kg/ha) is smaller than for the prior period[6].

Due to lower expected crop yields without use of agro-chemicals, less fertilizer is used in extensive cereal farming than for common agricultural practice. Nitrogen application, for instance, in wheat farming is about 30 kg/ha smaller for extensive than for common, medium intensive farming in Switzerland (e.g. Nemecek et al., 2001). Due to nonuse of agro-chemicals and lower fertilizer application, crop yields in extensive farming systems are smaller than for conventional management. Recent field trials (Basler et al., 2007) show that Swiss wheat yields, depending on the variety, are about ten to fifteen percent smaller for extensive than for conventional farming systems.

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[6] This decline in maize yield growth might be attributed to cross-compliance components, which protect soils and prevent excess in the fertilizer balance and led to major changes in farming practices since 1999 in Switzerland (Finger, 2008).

The results shown in Table 4 suggest that there have been only small yield increases for crops that face high shares of extensive farming systems because yields leveled off even though the share of extensive farming was relatively stable since the mid 1990's. This might indicate limited short term technological development in farming systems without use of agro-chemicals, for instance, because the adaptive capacity to changes in environmental conditions (e.g. increased weed and insect pressure) might be reduced and they can not benefit from the development of new and more effective agro-chemicals (Finger, 2008). This phenomenon is not unique to our study. Using sample data of German farms, Osterburg (2005) shows that cereal yields of participants in agri-environmental schemes increased less than the cereal yields of non-participants. However, the testing of such hypothesis requires the analysis of farm level data which is beyond the scope of our study.

The levelling-off of cereal yields has been attributed to the introduction of ecological direct payments that foster extensive cereal farming also by another study (BAFU, 2006). However, the observed differing development of yields, i.e. the levelling-off of yields for all cereals but maize, might be caused by other factors. Two factors are expected to be crucial: changes in the production area and differences in price developments. Changes in the production area comprise the shift from productive to less productive soils if extensive production (and the according direct payment) is adopted. Moreover, a particular direct payment scheme for all cereals but maize might foster a decrease of the area under maize and an increase in the remaining cereal producing acreage, respectively. An increasing area - for instance under wheat - might include less productive soils and thus reduce average yields. In order to analyze the latter issue, the annual area harvested (FAO, 2008) of the different cereals for the relevant period from 1991 to 2006 is compared. It shows that the area harvested for all crops but triticale decreased within this period. This is further underlined by a high positive correlation (significant at the 0.05 level) of the area harvested for all crops but triticale, which is negatively correlated with the other crops. Thus, no differences can be observed for the acreage of maize and of the remaining cereals that might have caused different development of yields. In order to examine the impact of price developments of analyzed crops on their differing yield development, price data for the period from 1991 to 2005 is used (FAO, 2008).

Decreasing output price levels are expected to cause decreasing yields, whereas increasing output prices might cause increasing yields relative to other crops. Because price levels in Swiss agriculture have been rather determined by agricultural policy than by the market, the observed price developments of the analyzed cereals are perfectly correlated (significant at the 0.01 level). The prices decreased by about 50% in the period from 1991 till 2005 for all cereals. In order to test the influence of changes in prices and acreage on yield levels, we employ a joint generalized least squares regression approach. For each crop, yield observations are regressed on price and acreage observations for the period from 1991 till 2005. The correlation between the error terms of the different regression equations is taken into account in the estimation procedure to improve the regression estimates (Zellner, 1963). It shows that the development of prices and harvested area significantly influenced crop yields only for rye (not shown). For the remaining crops, these variables had no significant impact on the development of yields. However, based on the here applied data, we can only raise the hypothesis that the introduction of ecological direct payments that foster extensive cereal farming led to a levelling-off of cereal yields in Switzerland. In order to test this effect on an adequate data base, further research should apply farm level data.

The observed levelling-off of yield growth pointed out in our study for some Swiss cereals might also be a prospect for future crop yield developments in other countries if less intensive or environmentally friendly farming practices are applied. For the European Union (EU), Schmid and Sinabell (2007) show that recent reforms of common agricultural policy will lead to a reduction of price levels and further decoupling that cause a decreased application of agricultural inputs such as nitrogen and pesticides. Thus, incentives to adopt extensive farming practices are increased by policy reforms in the EU, which might reduce future crop yield growth.

5. Discussion and Conclusion

Assuming linear trends, our analysis shows annual growth of 124 kg/ha for maize and 75 kg/ha for wheat in Switzerland. The estimate for maize is consistent with estimated annual yield growth in Germany of about 126 kg/ha. However, the estimated annual yield growth of wheat in Germany (99 kg/ha) is larger than our estimate for Switzerland

(Krause, 2008). The annual growth rates indicated by our study are much higher than trends estimated by Hafner (2003) on a global scale: 62 kg/ha per year and 43 kg/ha per year for maize and wheat, respectively.

For barley and rye we find increasing yield variability over time that might be caused by changes in climatic conditions and crop management. An example for the latter is the increased fertilizer application since 1960, which is expected to increase both, crop yields and yield variability. Increased climatic variability in Switzerland, e.g. the higher frequency of climatic extreme events such as heat waves, droughts and heavy rainfalls (e.g. Fuhrer et al., 2006), might have further increased the variability of crop yields. However, since increasing yield variability is indicated only for two crops in our analysis, this impact is not yet severe. The decomposition of changes in yield variability in management and climate related components (e.g. Iglesias and Quiroga, 2007) is beyond the scope of this paper because it requires regional data as Switzerland faces high spatial variability of climate and production structures. In our analysis, relative yield variability is even decreasing for oats and shows no significant trend for barley, maize, rye, triticale and wheat. Thus, increasing yield levels have more than offset the slightly increased yield variability.

The trends of crop yield growth identified in this study, which are particularly determined by technological development and agri-environmental policy, might indicate prospects of future crop yield development and thus of future food supply. Our results suggest linear crop yield growth for conventional farming systems but slowing yield growth if environmental friendly production methods such as extensive farming are widespread used. The latter is consistent with scenarios for future development of European crop yields applied by Ewert et al. (2005). They assume that if environmentally friendly production structures are applied in Europe, e.g. by the reduction of synthetic fertilizer and pesticides use, crop yields will show leveling-off in the future. The slowing crop yield growth observed in Switzerland supports these scenario assumptions and might thus be a prospect for future crop yield development in Europe.

Besides technological development and agri-environmental policy, climate change is expected to be an important determinant of future crop yield development. However, current analyses conclude only small impacts of climate change on Swiss cereal production at large. Finger and Schmid (2008) and Torriani et al. (2007) show that winter wheat yields at the Swiss Plateau will slightly increase in the future, in particular caused by increased CO2 concentrations. These studies show furthermore that climate change can reduce Swiss maize yields, as it might suffer from pronounced reductions in summer rainfall and increases in temperature. Moreover, the increased variability of future climate, such as the more frequent occurrence of heat waves and summer droughts (Beniston, 2004, and Fuhrer et al., 2006), might increase the variability of cereal yields. However, yield reductions as well as increased yield variability might be compensated or even overcompensated if adaptation actions such as shifts in seeding dates, the adjustment of the production intensity, the introduction of new varieties or irrigation are taken into account (Finger and Schmid, 2008, and Torriani et al., 2007).

Furthermore, the liberalization of agricultural markets might be an important driver of future changes in Swiss agriculture. Current agricultural price levels in Switzerland are much higher than in other European countries and are thus expected to decline if market liberalization takes place in the future. Taking both climate change and market liberalization into account, it shows that the latter might be much more important for future crop yield growth and the development of Swiss agriculture in general (Finger and Schmid, 2008, and Flückiger and Rieder, 1997).

In conclusion, future development of Swiss cereal yields might be determined by various factors. As it is shown by Ewert et al. (2005) for Europe at large, particularly future technological development is expected to far outweigh effects of climate change as it caused enormous yield increases in the last decades and will be the source of further yield increases in the future. Furthermore, agri-environmental policy and the development of agricultural prices are expected to be important determinants of future crop yield growth in Swiss cereal production.

The employed robust regression technique (Reweighted Least Squares) is valuable for further application because it enables robust and efficient coefficient estimation in presence but also in absence of outliers. The need for robust regression methods is even more pronounced if farm level instead of aggregated data is used, because these yield observations exhibit greater variability and more outliers than aggregated yield data.

Therefore, further research should take robust regression techniques into account if detrending of crop yields is required for further analysis.

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