Effect of output price volatility on agricultural land use

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Abstract

The EU's CAP reform to liberalize markets and decouple payments from production has led to increasingly volatile output prices, and therefore, more price and income risk. In this study, eight land use share equations are specified and estimated using regional data from 2000 through 2013. A multiple-equation panel data model is used to determine the contribution of increased price volatility and risk to land-use change. More specifically, it is investigated how relative perceived risk affects land use change. We found opposite effects between complementing and substituting land uses, leading to competition within the dairy sector and within crop production.

Keywords: *CAP, land-use change, panel data, price volatility, risk perception.*

Résumé

La réforme de la PAC de l'UE, visant à libéraliser les marchés et à découpler les paiements directs de la production, a entraîné une plus forte volatilité des prix de production et a provoqué, par conséquent, une augmentation du risque de prix et de revenu. Le but de ce travail est de présenter et évaluer huit équations concernant les modes d'utilisation des terres, en considérant les données régionales de 2000 à 2013. Un modèle à équations simultanées sur données de panel a été retenu pour mesurer l'impact de l'accroissement de la volatilité des prix et du risque de prix sur le changement d'affectation des sols. En particulier, nous avons focalisé l'attention sur le changement d'affectation des sols lié à la perception du risque relatif. Nous avons observé des effets opposés entre utilisations des terres complémentaires et de substitution, qui génèrent une concurrence au niveau du secteur laitier et de la production agricole.

Mots-clés: PAC, changement d'affectation des terres, données de panel, volatilité des prix, perception du risque.

1. Introduction

Over the past decade in the Netherlands, volatile output prices have led to fluctuating profitability of agricultural land and may therefore have affected land-use decisions. For a producer, the shadow price of land represents the land's marginal contribution to profit. If a producer has no constraints on land use, profit maximization occurs at the point where shadow prices are equal among all alternative land uses. However, the equality of shadow prices among land uses only accounts for expected output prices because producers do not know output prices at the time they choose their production activities, and must base their expectation on past experience. This causes uncertainty for the producer about the difference between the actual and expected output price, which may differ per activity and through time. For a risk-neutral producer uncertainty will not influence his production decisions. For a risk-averse producer, production activities with a high expected output price and a low profit variability are preferred. A risk-averse producer, faced with increased volatility in output prices, is therefore more likely to switch to less volatile production activities.

The European Union's Common Agricultural Policy (CAP) is shifting away from market and price support to liberalized markets and decoupled payments from production. This is likely to result in an increased volatility of output prices and hence, farm profits, which affects the competitive positions of agricultural and non-agricultural land uses (Ridier and Jacquet, 2002; Sckokai and Moro, 2006; Brady *et al*., 2009). However, because the degree of volatility is crop-specific, the effect on farm plans has so far remained unclear.

Competing agricultural and non-agricultural claims arise, especially in areas such as the Netherlands where land is scarce. In this paper our focus is solely on agricultural land use, ignoring competition with other sectors and taking the total (decreasing) amount of agricultural land as given.

There is an extensive literature on the estimation of models that analyze multiple-output supply decisions and agricultural land allocation decisions. Broadly, two lines of thinking can be distinguished: estimating a system of output supply, input demand, and land-use equations (Coyle, 1992; Oude Lansink, 1999; Sckokai and Moro, 2006), and estimating land-use response equations (Moore and Negri, 1992; Wu and Segerson, 1995; Fezzi and Bateman, 2011).

Estimating a system of output supply, input demand, and land-use equations has been applied by Coyle (1990,; 1992,; 1999), who combined the effects of risk aversion, price uncertainty, and yield uncertainty on crop production decisions in mean-variance duality models of production. Oude Lansink (1999) elaborated on Coyle's work by using a linear mean-variance utility function that incorporated risk to determine the input demand, output supply, and area allocation simultaneously among various crops. More recently, Sckokai and Moro (2006) adapted Coyle's frame-

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work to account for the increased output price volatility caused by CAP reforms in a study of crop production.

Estimating land-response equations has been applied by Moore and Negri (1992) to develop land and water allocation equations based on a flexible functional form of a multi-crop production function. Wu and Segerson (1995) elaborated on this model by adjusting it to account for land heterogeneity.

The two approaches were integrated by Chambers and Just (1989), who used a two-step modeling framework: this approach allocates land among different production activities after the optimal levels of outputs and inputs have been determined. Arnade and Kelch (2007) extended this framework by deriving shadow price equations for crop areas. Fezzi and Bateman (2011) used the Chambers and Just framework to establish a joint profit function to derive equations for "land-use share" (the proportion of the land area allocated to each use) that can be estimated as a system. There also exists a great body of literature on yield risk (Just and Pope, 1979; Chavas and Holt, 1990). However, in order to focus on price risk, we choose to ignore yield risk. Estimating land-use response equations that not only account for the effect of price uncertainty on its own land use (e.g. price uncertainty of wheat on the land use of wheat), but also on alternative land uses (e.g. sugar beets) has not yet been undertaken.

The purpose of this paper is to assess the effect of volatile agricultural output prices on changes in agricultural land use since 2000 in the Netherlands by estimating a system of land-response equations. The land-response equations are based on a restricted profit function, taking both risk and farm technology into account. We used data on 66 Dutch agricultural regions from 2000 through 2013 to analyze the land-use decisions of producers.

In the next section we establish land use share functions that account for the risks that result from increased price volatility. Moreover, we hypothesize that the effect of agricultural outputs being complements and substitutes affects land use decisions. Next, we describe the study area and data sources. We then develop an empirical model in which the producer optimizes his profit by allocating land among different uses while accounting for risk. In the final sections, we econometrically estimate the land-use share equations, discuss the results, provide a general discussion, and present the main conclusions drawn from our study.

2. Theoretical Framework

Building upon the work of, amongst others, Chavas and Pope (1982), Coyle (1990, 1992) and Wu and Segerson (1995), we derive a system of land use share equations based on a utility maximizing producer. We assume a profit function with multiple outputs (land uses or crops), where the producer must decide how to allocate his/her hectares among different land uses in order to maximize total profits (Wu and Segerson, 1995). The profit function is elaborated by accounting for risk in production decisions; the producer therefore becomes a utility maximizer (Oude Lansink, 1999). Expected utility is determined by the expected profit, the variance of profit, and the coefficients of absolute risk aversion per crop (see e.g. Coyle, 1990, 1992). Based on utility maximization we derive land-use share functions that represent the proportion of the land that producer h allocates to land use i in year t:

$$s_{hit}^{U} = s_{hit}^{U}\left(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, \mathbf{Vp}\right) = \frac{n_{hit}^{U}}{N_{ht}} \qquad h=1,\dots,H;\ i=1,\dots,I;\ t=1,\dots,T. \tag{1}$$

The land-use share of producer h for crop i in year t (s_{hit}^{U}) depends on all expected output prices ($\hat{\mathbf{p}}_t$) and known variable input prices ($\mathbf{w}_t$) in year t, yields ($\mathbf{q}_{ht}$) of producer h in year t, fixed input quantities ($\mathbf{z}_{ht}$) of producer h in year t, the variance of prices (**Vp**), and the degree of risk-aversion. The land use shares equal the number of hectares n_{hit}^{U} of producer h allocated to crop i in year t divided by the total number of hectares N_{ht} of producer h in year t. When **Vp**=0, the land-use share equation for the utility-maximizing producer equals the land-use share equation for the profit-maximizing producer. For the mathematical derivation from the profit function to the land use shares, we refer the reader to the Appendix.

Ratio of coefficient of variations

Figure 1 shows that for all output prices there is some degree of volatility. We assume that, when determining optimal land use, the producer looks at the relative price volatility between crops; hence the variation of a crop compared with the variation of the alternative crops. To take this into account, we take the ratios of the coefficients of variation as elements of **Vp**:

$$v_{ir} = \frac{\sigma_r/\mu_r}{\sigma_i/\mu_i} = \frac{Cv_r}{Cv_i} \qquad i,r=1,\dots,I;\ i\neq r\ , \tag{2}$$

where Cv_r is the 3-year moving average of the coefficient of variation, the standard deviation divided by the average, of the output price of the alternative (substitute or complement) crop and Cv_i is the 3-year moving average of the coefficient of variation of the output price of the crop of interest. Hence, in 'the ratio of the coefficients of variation' the CV of the alternative crop is in the numerator and that of the crop of interest in the denominator.

We used coefficients of variation instead of variances because, in comparison to variance, the coefficient of variation is a unitized measure of risk. So, dividing the ratio of two coefficientcoefficients of variations (see equation 2) does not lead to a violation of the homogeneity assumption.

Substitutes and complements

In the model presented, land use change depends on the factors determining the land shares, i.e. expected output prices, variable input prices, yields, quantities of fixed factors and the variance of output prices. Implicit is also farm technology relevantce, showing to what extent the producer is able to adjust activities within his enterprise. One aspect of farm technology is whether production activities are complements or substitutes. Complements are defined as those activities that are in joint supply, either because of crop rotation requirements or because one output is needed as an input in producing another output. Substitutes are defined as (sets of) activities that are rival to each other.

For arable production in the Netherlands, the common rotation system is the joint production of cereals, potatoes and sugar beets. For dairy production, fodder maize and grassland can be viewed as complementary to milk production. When facing a larger expected utility, it is likely to be easier for a producer to switch activities within these two sets of production rather than between them.

Based on the ratios of coefficients of variation we can examine whether two land uses are substitutes or complements. For substitutes and in case of risk-aversion a producer will increase the share of a crop when the ratio of coefficients of variation increases (the coefficient of variation of the crop being in the denominator). For complements the opposite is true.

3. Data

We divided the Netherlands into 66 agricultural regions using an existing classification based on homogeneity of soil types (Helming, 2005; Helming and Reinhard, 2009). One of the advantages of using this classification for the types of agricultural regions is the relative homogeneity of the soil within these regions. All regions can be classified based on the soil type (clay, sand, or mixed soil that includes peats and loams). Different soil types generate different crop yields and therefore attract different production activities.

We aggregated farm structure survey (FSS) data for all farm households in the Netherlands from 2000 through 2013 into the 66 agricultural regions (Statistics Netherlands, 2013). Based on the available data, we defined eight agricultural outputs as the different types of land use. Specifically, we grouped the agricultural land uses into cereals, grassland, sugar beets, potatoes, fodder maize, onions, vegetables, and "other" (Table 1). In the Netherlands, grassland is mainly used for dairy production. Although beef and other cattle are also grazed in Dutch grassland areas, they account for a small proportion of the total grassland use. Moreover, nitrate regulations require a minimum amount of land per cow and thereby make dairy farming heavily dependent on the availability of grassland. Thus, in the rest of the article, we will refer to grassland exclusively in the context of dairy cattle.

For each year and each region, we calculated the amount of land (ha) for each land use using Dutch FSS data. We converted that area (ha) into land-use shares by dividing the area of each land use in a given region and year by the corresponding total amount of agricultural land. Table 2 summarizes the descriptive statistics for the agricultural land uses for the first and last years of the panel and for the panel as a whole. Table 3 summarizes the descriptive statistics for the explanatory variables.

The aggregation from individual crops to the eight land uses led us to use price indices instead of absolute prices for each land use. We first standardized all nominal absolute prices using 2000 as the base year before we normalized output prices by dividing them by the output price index of fertilizer (Eurostat, 2014; LEI, 2014).

Unfortunately, it was not possible to retrieve all data on output and input prices from the same database. Therefore, data on absolute output prices for several land uses (cereals, grassland, potatoes, fodder maize, and onions) were retrieved from LEI (2014), whereas data on absolute output prices for the other land uses (sugar beet, vegetables, and other) were retrieved from Eurostat (2014). Data on the input price of pesticides was retrieved from LEI (2014), whereas data on the input price of fertilizer was retrieved from Eurostat (2014). We only include fertilizer and pesticides as variable inputs because all selected crops require these inputs.

For some land uses, we chose a proxy for output price (Table 1). For onions, there was a limited amount of price data available. This led us to replace the output prices for onions from 2000 through 2004 with the corresponding prices from 1995 through 1999. The resulting output price indices are shown in figure 1. As a measure of the expected output prices, we calculated an annual 3-year moving average (ending with the year previous from to the year being studied) of the output prices.

Producer expectations about price fluctuations are based on past experience. We assumed that price variation was equal across regions. The coefficient of variation of the

Table 1 - *Specification of land uses and their outputs.*

Land Use	Crops	Output price and yield
Cereals	Winter wheat, Summer wheat	Summer wheat
	Winter barley, Summer barley	
Grassland	Permanent grassland	Milk
	Temporary grassland	
Sugar beets	Sugar beets	Sugar beets
Potatoes	Seed potatoes,	Main crop potatoes
	Consumption potatoes	
Fodder maize	Fodder maize	Fodder maize
Onions	Seed onions, Seed onions	Seed onions
Vegetables	Endives, cauliflowers, leeks,	Cauliflowers
	broccoli, Brussels sprouts	
Other	All other crops	Overall index

Table 2 - *Summary statistics for agricultural land uses at the start and end for the Netherlands by year and whole panel by region and year (2000-2013).*

	2000		2013		Whole panel				
Share[a)]	Absolute (1000 ha)	Share	Absolute (1000 ha)	Share	Mean	S.D.	Min.	Max.	share non-zero obs
Cereals	183.64	0.10	182.37	0.10	0.10	0.11	0.00	0.41	0.99
Grassland	1010.02	0.52	982.95	0.54	0.53	0.27	0.09	0.99	1.00
Sugar beets	110.95	0.06	73.19	0.04	0.05	0.05	0.00	0.21	0.97
Potatoes	180.16	0.09	155.82	0.08	0.08	0.09	0.00	0.40	0.99
Fodder maize	205.30	0.09	229.74	0.11	0.10	0.08	0.00	0.40	1.00
Onions	19.27	0.01	28.17	0.01	0.01	0.02	0.00	0.12	0.84
Vegetables	6.44	0.00	6.70	0.00	0.00	0.01	0.00	0.06	0.93
Other	235.68	0.14	188.67	0.12	0.13	0.11	0.00	0.62	1.00
Total	1951.45	1.00	1847.61	1.00	1.00				

[a)] *(absolute = the actual area; share = absolute area divided by the total area)*

normalized output price indices over the 3 years previous to the year being studied was used as a proxy for the expected variation in output prices. In addition to the output and input prices, we included the quantity of fixed inputs, yields and the presence of direct payments as explanatory variables. As a proxy for fixed inputs, we used the average size of a farm in a region, which was obtained from the FSS data. Size is measured by the standardized annual revenue of a specific production type per hectare of land or per animal. The average size was calculated as the sum of all farm sizes in a region, divided by the number of farms in the region and subsequently converted into an index. For each land use, the production (yield in kg/ha; Table 3) was converted into an index value similar to the way we did for output prices (with the value in 2000 = 100). The presence of direct payments is referenced to as a dummy trend, starting in 2006 when direct payments were introduced, and taking the value zero prior to 2006.

The descriptive statistics in Table 2 show that average land use shares of the different agricultural land uses over all regions have changed only slightly over time. However, some land uses have changed considerably more than others. In particular, the area of sugar beets, potatoes and other decreased, whereas the area of grassland and fodder maize. This indicates a tendency towards dairy production. Grassland remained the main land use throughout the study period, with a share of more than 50% of the total agricultural land. The columns representing standard deviations, minimum and maximum shares of land use in Table 2 indicate large regional differences in land uses. This may be because of the division of regions based on homogeneity of soil. In varying degrees, almost all land uses are prevalent in each region during the whole period (see last column Table 2).

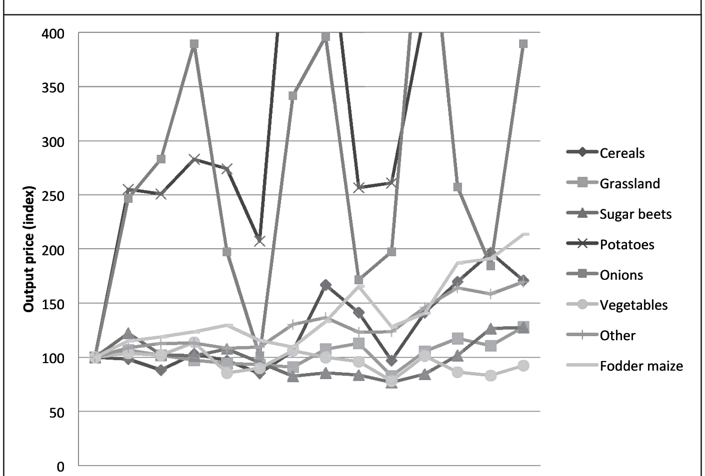
Compared to the relatively small changes in the land-use shares, figure 1 shows relatively large changes in output prices. The output prices seemed to follow some common trends in their fluctuations, such as decreases between 2003 and 2005 and between 2007 and 2008 and an increase over the last two years. However, large differences in the volatil-

Table 3 - *Summary statistics of explanatory variables over the whole time period (2000-2013).*

Land-use	Mean	Std. Dev.	Min.	Max.
Expected output price indices (normalized by the price of fertilizer)				
Cereals	0.838	0.134	0.624	1.126
Grassland	0.770	0.182	0.493	1.159
Sugar beets	0.770	0.208	0.451	1.189
Potatoes	2.500	0.633	1.511	4.023
Fodder maize	0.930	0.231	0.600	1.472
Onions	2.015	0.413	1.445	3.128
Vegetables	0.818	0.156	0.530	1.115
Other	0.876	0.113	0.653	1.069
Expected yield indices (/100 in estimation for scaling purposes)				
Cereals	100.910	3.382	92.647	104.902
Grassland	103.237	4.099	94.691	109.078
Sugar beets	106.949	8.335	91.952	127.030
Potatoes	94.576	1.904	90.386	97.193
Fodder maize	106.612	3.987	100.480	115.588
Onions	92.550	3.282	85.323	101.882
Vegetables	108.451	7.744	83.548	218.187
Input price indices (normalized by the price of fertilizer)				
Pesticides	0.724	0.147	0.450	1.000
subsidies	0.571	0.495	0.000	1.000
Fixed cost indices (/100 in estimation for scaling purposes)				
Farm size	118.000	18.000	48.000	198.000
Coefficient of variation of the normalized expected output price indices [a)]				
Cereals	0.182	0.121	0.058	0.469
Grassland	0.124	0.074	0.044	0.309
Sugar beets	0.129	0.077	0.021	0.329
Potatoes	0.397	0.200	0.063	0.816
Fodder maize	0.116	0.060	0.037	0.200
Onions	0.542	0.155	0.242	0.840
Vegetables	0.121	0.067	0.030	0.340
Other	0.121	0.093	0.047	0.314

[a)] For scaling purposes and clarity of estimation results, the ratio of coefficients of variation areis divided by 10.

Figure 1 - *Changes in nominal output prices from 2000 to 2013. Values are normalized by setting the price in the base year (2000) to 100.*



ity of the output prices can be observed. Output price volatility was especially high for onions and potatoes, both in terms of the largest increase between two years (respectively 237.5 and 172.7 percent) and the largest decrease between two years (respectively -56.7 and -79 percent), compared to an average increase of 31.8 and an average decrease of 15.7 percent over all land uses between two years.

The large differences in output price volatility are reflected in the coefficients of variation of output prices (Table 3). Potatoes and onions experienced much larger price variations than other land uses.

4. Empirical Model

As indicated in equation 1 the allocation of land among different production activities for a utility-maximizing producer does not depend only upon output and input prices, and fixed input quantities, but also depends upon the variation in output prices in relation to farm technology and the producer's degree of risk-aversion. Given the land-use share equations for a utility-maximizing producer developed in the theoretical model, we have specified the following reduced-form land-use share equations:

$$\begin{aligned} S^*_{hit} = \varphi_{hi} + \sum_{j=1}^{J}\beta_{ij}x_{jt} + \sum_{m=1}^{M}\rho_{im}q_{mt} + \sum_{k=1}^{K}\gamma_{hk}z_{kht} \\ + \omega_i g_t + \sum_{r=1}^{R}\delta_{ir}v_{irt} + \lambda_i T_t + u_{it} \end{aligned} \qquad h=1,\dots,H;\ i=1,\dots,I;\ t=1,\dots,T \qquad (3)$$

Where S^*_{hit} represents the N_{ht} land-use shares of crop i in region h in year t; φ_{hi} represents the region-specific intercept for region h and land use i; β_{ij} represents the coefficients for normalized input and output prices j for crop i; X_{jt} represents the normalized input and output prices j in year t; ρ_{im} represents the coefficients of yields m for crop i; q_{mt} represents the yields m in year t; γ_{hk} represents the coefficients of fixed factors k for region h; z_{kht} represents the fixed input factors k for region h in year t; ω_i represents the coefficient for crop i for the presence of direct income payments, g_t represents the direct income payments dummy trend, δ_{ir} represents the coefficients for the ratios of the coefficients of variation of the expected prices r for crop i; v_{irt} represents the ratios of the coefficients of variation of the expected alternative prices r with respect to expected prices i in year t; λ_i represents the coefficient of crop i for the trends; T_t represents the time trend; and u_{it} represents the unobservable effects that affect land-use change for crop i in year t.

Equation 3 specifies the share of land use for each crop i in region h in year t. Because only relative prices matter, the model has been made homogeneous of degree zero by normalizing the standardized output prices and the standardized price of pesticides using the price of fertilizer. Each land use share equation only includes expected output price of its own land use and not expected output prices of alternative land uses in order to avoid multicolllinearity. Due to data limitations, the fixed input quantities (z_{hkt}) are only represented by the average farm size per region per year and not allocated to individual land uses. A time trend has been included to account for crop-specific trends in land-use shares.

We assume the covariances of output prices to be zero. In reality, the covariances are not zero, but the large amount of covariance values caused multi-collinearity problems. For a producer, the covariance of alternative products may be of importance in deciding upon land allocation. However, by estimating the effect of the ratios of the coefficients of variation all alternative land uses are taken into account.

We tested for censoring from below, meaning that there is a lower bound of zero for all land use shares. In case many land use shares actually take the value zero this could lead to inconsistent estimates of the parameters (Fezzi and Bateman, 2011). The results, provided in Table 2, show that censored observations are only present for vegetables, but not enough that inconsistent estimates of the parameters may be expected. This, together with the few non-zero observations for crop shares (see Table 2), means that we do not have to take sample selection problems into account. We therefore estimated the land-use share equations as a system using the seemingly unrelated regression (SUR) technique taking into account that the disturbances from different share equations are likely to be correlated because of common unobservable factors (Fiebig, 2001). This correlation could have several causes, such as weather, policy changes affecting the agricultural sector as whole, or economy-wide shocks. The yearly observations over the same study areas lead to a panel that required a fixed-effects transformation of the SUR regression. Because we deal with national values for both price and yield indices, a fixed effects transformation using deviations from the mean was not possible. We therefore chose a first-difference transformation on the model of the eight land-use shares:

$$\begin{aligned} \left(S^*_{hit} - S^*_{hit-1}\right) = \sum_{j=1}^{J}\beta_{ij}\left(x_{jt} - x_{jt-1}\right) + \sum_{m=1}^{M}\rho_{im}\left(q_{mt} - q_{mt-1}\right) + \omega\left(g_t - g_{t-1}\right) \\ + \sum_{k=1}^{K}\gamma_{hk}\left(z_{hkt} - z_{hkt-1}\right) + \sum_{r=1}^{R}\delta_{ir}\left(v_{irt} - v_{irt-1}\right) + \lambda_i + \left(u_{it} - u_{it-1}\right) \end{aligned} \qquad h=1,\dots,H;\ i=1,\dots,I;\ t=1,\dots,T \qquad (4)$$

Equation 4 implies that the intercept (φ_{hi}), which represents the region-specific effect, cancels out. The new intercept λ_i represents the coefficient of the crop-specific trend in equation 3. The transformed explanatory variables are composed of the first-differenced expected output prices ($\hat{p}_{it}$), first-differenced input prices, first-differenced yields per hectare (q_{mt}), first-differenced average farm size (z_{hkt}), first-differenced dummy trend representing the presence of direct income payments (g_t), and the first-differenced ratios of the coefficients of variation ($v_{irt} - v_{irt-1}$)[1]. Note that the dummy time trend for government subsidies transforms in-

[1] Note that with first-differencing the panel is reduced by one year; i.e. observations start as of the second year of observations in the original panel. Moreover, first-differencing only occurs between time periods and not between regions or land uses.

to a dummy representing the presence of direct payments. Tables 2 and 3 list the dependent and explanatory variables and their descriptive statistics.

Because all land-use shares together must sum to 0 in the first-differenced model, estimating all the land-use equations together results in a singular covariance matrix of error terms. While there are various ways to handle this singularity problem (Takada *et al.*, 1995), we decided to drop the residual equation 'other' from the system (Fezzi and Bateman, 2011). The residual equation can then be recalculated because, by definition, the land-use shares must sum to 1.

5. Results

We tested the contemporaneous correlation using the Breusch-Pagan test. The null hypothesis (i.e., no contemporaneous correlation) was rejected at the 1% level ($\chi^2(21) = 274.101$ and $P < 0.001$). This suggests that there is significant correlation because common elements exist in the seven equations that relate the equations through their residuals. The strongest correlations occurred between the residuals for wheat and meadows (33%) and potatoes and onions (22%). We tested for groupwise heteroskedasticity using the Lagrange Multiplier test. The null hypothesis (i.e., no groupwise heteroskedasticity) was rejected at the 1% level of significance for each of the seven equations. This means that the variances are constant over time within the equations, but differ between them. We tested for groupwise autocorrelation using the Durbin-Watson test. For all land uses the null hypothesis (i.e., no-autocorrelation) was rejected at the AR(1) level. This result means that there is either positive or negative autocorrelation and that the different error terms are correlated. Hence, statistical efficiency increases by estimating the seven equations as a system, and SUR is therefore the appropriate estimation method. Without SUR, the observed heteroskedasticity and autocorrelation would lead to biased and inconsistent estimates.

Table 4 summarizes the estimated regression coefficients for the seven land-use share equations. The table consists of two parts. The upper part of the table reports the regression coefficients of all variables except those relating to risk. The lower part of the table reports the regression coefficients for perceived risk due to price volatility. Moreover, the χ^2 value for all equations except for vegetables was significant at the 1% level. For vegetables, the χ^2 value was significant at the 5% level. This means that at least one of the regression coefficients in the model does not equal zero. Hence, we can be confident that the dependent variable is correlated with the individual variables. The coefficients of the land-use equations were generally small, indicating that land-use change is a slow process. We will discuss the estimation results for all variables except those relating to risk in the next section.

Non-risk estimation results

An increase in the expected output price of a particular land use is expected to lead to an increase in the share of that particular land use. Only grassland showed a negative and significant coefficient (Table 4), which supports this hypothesis. In the Netherlands, grassland is mainly associated with dairy farming. Dairy farming has been subject to quota restrictions for the whole observation period;, making it more difficult to increase milk production following an increase in the output price of milk. Using the expected prices and land use shares of 2013 we calculated the elasticities with respect to output price of the land use shares. Table 5 shows the resulting percentage change in land shares, taking into account the effect of a 1% increase in a particular output price on its own and on alternative land use shares. All percentage changes in land share are inelas-

Table 4 - *Estimation results (regression coefficients) using the system of land use* [a), b), c)].

	Cereals	Sugar Beet	Potatoes	Grassland	Fodder Maize	Onions	Vegetables
Output price	0.022 (0.012) *	0.039 (0.008) ***	0.025 (0.005) ***	-0.230 (0.056) ***	0.010 (0.005) *	0.001 (0.001) ns	0.002 (0.005) ns
Yield per ha	0.026 (0.013) **	-0.132 (0.021) ***	0.065 (0.031) **	-0.956 (0.181) ***	-0.085 (0.067) ns	-0.059 (0.011) ***	0.000 (0.000) ns
subsidies	0.001 (0.002) ns	0.004 (0.001) ***	-0.014 (0.003) ***	0.015 (0.003) ***	-0.001 (0.002) ns	0.002 (0.001) ***	-0.000 (0.000) ns
Pesticide price	-0.003 (0.008) ns	-0.001 (0.002) ns	0.081 (0.012) ***	-0.144 (0.021) ***	-0.014 (0.009) ns	0.005 (0.001) ***	0.002 (0.001) ns
Farm size	-0.023 (0.007) ***	-0.009 (0.002) ***	0.003 (0.003) ns	0.016 (0.014) ns	0.002 (0.005) ns	0.004 (0.002) **	0.003 (0.002) *
Constant	0.002 (0.002) ns	0.002 (0.001) ***	0.010 (0.002) ***	-0.027 (0.006) ***	0.002 (0.001) ***	-0.001 (0.001) ns	-0.000 (0.000) ns
Ratio of coefficients of variation (rows represent nominator, columns denominator)							
Cereals		-0.010 (0.003) ***	0.299 (0.053) ***	-0.047 (0.017) ***	0.018 (0.015) ns	0.019 (0.009) **	0.007 (0.003) ***
Sugar Beet	-0.309 (0.096) ***		-0.132 (0.023) ***	-0.019 (0.015) ns	0.059 (0.014) ***	-0.061 (0.016) ***	0.006 (0.003) *
Potatoes	0.034 (0.012) ***	-0.017 (0.003) ***		-0.034 (0.011) ***	0.023 (0.004) ***	-0.046 (0.009) ***	-0.002 (0.002) ns
Grassland	0.442 (0.130) ***	0.061 (0.008) ***	0.043 (0.031) ns		0.004 (0.006) ns	0.051 (0.037) ns	-0.018 (0.016) ns
Fodder Maize	-0.576 (0.166) ***	0.012 (0.004) ***	-0.465 (0.072) ***	-0.357 (0.025) ***		0.068 (0.016) ***	0.012 (0.005) **
Onions	0.056 (0.018) ***	0.008 (0.001) ***	0.112 (0.021) ***	-0.022 (0.004) ***	-0.017 (0.002) ***		-0.000 (0.001) ns
Vegetables	-0.088 (0.026) ***	-0.051 (0.006) ***	-0.399 (0.073) ***	0.135 (0.027) ***	-0.001 (0.007) ns	-0.131 (0.018) ***	
Other	0.097 (0.036) ***	0.076 (0.014) ***	0.510 (0.080) ***	-0.387 (0.062) ***	0.015 (0.016) ns	0.047 (0.021) **	0.010 (0.009) ns

[a)] In the lower half of the table, the values equal the variance of the alternative crop (listed in the rows of the table) divided by the variance of the current crop (listed in the columns of the table).
[b)]Standard error in parentheses.
[c)] Where (*), (**)and (***) represent significance 10, 5 and 1% level respectively, and ns means not significant.

tic with respect to its output price. This is as expected; land use change is a slow process and is dependent on many other factors such as farm technology. Sugar beet and potatoes show the highest percentage change in land share (respectively 0.514 and 0.692 percent), grassland the lowest (-0.231 percent).

Yield per ha is assumed to have a positive effect on the land use share because yield increase makes producing the crop more profitable. For cereals and potatoes an increase in the expected yield leads to a significant increase in land-use share. For sugar beet, grassland and onions, an expected yield increase has a significant negative effect. Again, for both sugar beet and grassland, this may have to do with the quotas, restricting the ability to increase yields. For onions, this result might be counter-intuitive, but may be caused by the large fluctuations in yield for this crop.

When subsidies are completely decoupled from production, they should not alter the production plan (Hennessy, 1998). However, production decisions may be affected indirectly because of the so-called *wealth effect*, increasing a farmer's wealth and thereby reducing his level of risk aversion (Finger and Lehmann, 2012; Hennessy, 1998). Previous studies found that this may have some impact on crop allocation (Sckokai and Moro, 2009; Koundoury *et al.,* 2009). This would mean that due to the single farm payments (SFP), farmers are more willing to cultivate crops with a large price volatility. We find a positive and significant effect for cereals, sugar beet and grassland and a negative and significant effect for potatoes. Due to the decrease in the share of potatoes, a crop with large volatility, we do not find indication of a wealth effect. For grassland and sugar beet, the increase in share may have to do with the fact that the introduction of SFP was accompanied by a reduction in production restrictions. The trend for subsidies may therefore not only represent the introduction of SFP, but also the wider on-going liberalization of the CAP.

An increase in the price of pesticides is expected to lead to a decrease in the share of any land use that uses pesticides at a high intensity, but to an increase in the land-use share for a land use that uses pesticides at a low intensity. For grassland, the price of pesticides had a significant negative coefficient (Table 4). In contrast, potatoes and onions have a significant positive coefficient for pesticides. If the price of pesticides increases, this means that it becomes more favorable to cultivate these crops. Because fertilizer and pesticide use are positively correlated in intensive agriculture, this reasoning is in line with that of Fezzi and Bateman (2011), who reported that the price effect of fertilizer depended on whether the crop was nutrient-intensive or not.

Table 5 - *Elasticities of land use with respect to price.*

	elasticity
cereal	0.174
grassland	-0.231
sugar beet	0.514
potatoes	0.692
fodder maize	0.079
onions	0.119
vegetables	0.357

Since fixed inputs are not crop-specific we neither expect positive nor negative coefficients for average farm size. The coefficients representing average size showed little effect on the land-use shares (i.e., all values >-0.023 and <0.016; Table 4). For cereals, sugar beet, onions and vegetables, small significant effects were found.

The constant represents the overall trend in the land-use shares of the different crops. There was a positive and significant trend for sugar beet, potatoes and fodder maize and a negative and significant effect for grassland (Table 4).

Risk estimation results

The lower part of Table 4 reports the ratios of the coefficients of variation of the prices of two land uses as a measure of perceived risk due to the expected price volatility of the two land uses. The advantage of using the ratios of coefficients of variation rather than variances and covariances results from the fact that it accounts for the risk-averse producer who compares the alternative crop with the current crop. In the lower half of Table 4, the values equal the coefficient of variation of the alternative crop (listed in the rows of the table) divided by the coefficient of variation of the current crop (listed in the columns of the table). We tested each of the land use share equations for model differences with and without the ratios of the coefficients of variation using the likelihood ratio test. For all land use shares, except for vegetables, the null hypothesis was rejected at the 1% level. For vegetables the null hypothesis was rejected at the 5% level. Hence, test results showed that adding the ratios of the coefficients of variations to the model significantly improved the model fit. The results show many significant positive and negative coefficients, indicating that the ratios of the coefficients of variation successfully captured differences in the perceived risk. This is consistent with previous work by Sckokai and Moro (2006) that highlighted the impact of cross-crop effects on both the relative price and the variability of income.

Suppose we have the ratio of coefficients of variation (CV) of the output prices of two crops: CV crop Y / CV crop X. A positive sign implies that an increase in the ratio leads to an increase in the share of land allocated to crop X. So, for a risk-averse producer this means that when the price volatility of crop Y increases compared to that of crop X, the land share of crop X increases. This may imply that crops X and Y are substitutes. With complements or risk-loving producers, an increase in the relative price volatility of crop Y leads to a reduction in the land share of crop X. So, in case of complements, the coefficient has a negative sign. Hence, the likelihood for land use change depends on whether the crops are complements or substitutes and on the degree of risk aversion perceived by the producer.

For cereals (column 1 of Table 4), the ratio of the coefficients of variation with respect to sugar beet, fodder maize and vegetables showed a negative and significant coefficient. With respect to sugar beet, the negative sign implies that cereals and sugar beets are considered complements. This means that a smaller area of cereals would be grown if the price variation of beets increases compared to the price variation of cereals. This result is as expected because the most common crop rotation scheme in the Netherlands involves cereals, sugar beet and potatoes. The ratios of the coefficients of variation with respect to potatoes, grassland, onions and other show positive effects at the 1% significance level. This means these crops are substitutes for cereals. More relative price variation for these crops leads to an increase in the land share of cereals. For potatoes this result is unexpected. A possible reason may be that especially seed potatoes are also grown outside the common crop rotation of cereals, sugar beets and potatoes.

For sugar beets (column 2 of Table 4), the ratios of the coefficients of variation with respect to cereals, potatoes and vegetables were significant and negative, indicating that these are complementary products because of crop rotation requirements. Grassland, fodder maize, onions and other had a significant and positive effect, indicating that they are substitute products.

For potatoes (column 3 of Table 4), sugar beets, fodder maize and vegetables were complements. Sugar beet is a complement because of crop rotation requirements, whereas onions were substitutes. Cereals does not show the expected negative sign, whereas fodder maize does not show the expected positive sign. A possible explanation may be that rotation schemes only allow limited cultivation of potatoes, which leads farmers to rent land from dairy producers to cultivate potatoes.

Grassland and fodder maize are production activities that are related to dairy production. For grassland (column 4 of Table 4), the ratios of the coefficients of variation for fodder maize had a large negative and significant effect. This is expected, because both are grown for dairy production and can therefore be seen as complements. Also, potatoes can be seen as a complement as discussed previously. The ratio of coefficients of variation of vegetables showed a positive and significant effect, meaning that they can be seen as substitutes. For the other crops, onions and cereals, the estimated coefficients were negative and significant.

For fodder maize (column 5 of Table 4) the estimated coefficients were low and often not significant. A possible explanation for this could be milk quotas, which have been enforced throughout Europe as part of the CAP and are still binding in the Netherlands. If producers produce at the quota level, a change in profit will not directly lead to a change in land use. Previous studies showed that quota hamper changes in land use (Huettel and Jongeneel, 2011; Piet *et al.*, 2012). Another explanation may be that land used for dairy production is more difficult to change compared with land used for crop production. This is due to the relatively large amount of fixed capital required for dairy production and the fact that a large part of the soils in the Netherlands are not suitable for crop production. Significant coefficients are however observed for sugar beets and potatoes, acting as a substitute, and for onions, acting as a complement.

For onions (column 6 of Table 4), the volatility in prices is so high (figure 1) that we argue that the degree of risk the crop carries is more important than being part of a crop rotation system. Onions are the smallest land use; therefore producers may not be fully specialized in producing onions. This may lead producers to set aside some of their land for risk-loving behavior. The ratios of the coefficients of variation of onions with sugar beets, potatoes, and vegetables had significant negative effects, indicating risk-loving behavior.

For vegetables (column 7 of table 3), almost none of the ratios of the coefficients of variation were significant. This is consistent with our idea that vegetables do not function in a common rotation scheme with the other crops considered and that changes in vegetable production largely take place within its own category. Nonetheless, we found low, but significant and positive values for cereals, sugar beet and fodder maize.

Discussion and Conclusions

The European Union's CAP is shifting away from market and price support towards market liberalization and decoupled payments. The resulting increasingly volatile output prices and farm incomes pose challenges to agricultural producers that affect the competitive positions of various agricultural land uses. The objective of the present study was to assess the effect of volatile agricultural output prices on changes in agricultural land use since 2000 in the Netherlands.

Our analysis used data on 66 Dutch agricultural regions from 2000 through 2013 to analyze land-use decisions. We defined eight land use activities: production of cereals, grassland, sugar beets, potatoes, fodder maize, onions, vegetables, and other crops. For each land use, we established restricted profit functions that depended on expected output prices, variable input prices, the presence of direct payments, crop yields, the quantity of fixed inputs, and the ratios of coefficient of variation of expected output prices with those of alternative crops. Coefficients of variation were used in order to obtain a unitized measure of risk. Using ratios enabled us to distinguish between complements and substitutes in farmer's activities. Land-share equations were estimated using a multiple-equation panel-data model to determine the contribution of increased price volatility to land-use change.

Our estimation of the non-risk variables showed that for all land-use shares except for grassland, an increase in the expected output price of a particular land use led to an increase in the share of that particular land use. This is consistent with previous research, which showed significant positive effects of output price on land-use responses and suggests that price expectations are important in land-use decision-making (Sckokai and Moro, 2006; Fezzi and Bateman, 2011). Regression coefficients for expected yield showed negative results for land uses where the level is dependent on quota restrictions, namely sugar beet and grassland. For these two land uses, the introduction of single farm payments leads to an increase in their share of land. However, this result may be related to easing the production restrictions for these products that accompanied the introduction of the single farm payments. Therefore, the variable may be more likely to represent the on-going liberalization of the CAP. An increase in the price of pesticides showed variations in their effects, suggesting that an increase in the price of pesticides favors land uses that use these chemicals less intensively. The average farm size in a region had little to no effect on the land-use shares.

The ratios of the coefficients of variation of the prices of two alternative land uses can be used as a measure of expected relative price volatility. Two main conclusions can be drawn based on the present results. First, the results show many significant positive and negative coefficients, indicating that relative price variation matters and serves as a proxy for the degree of perceived risk. Risk-loving behavior was observed for onions and potatoes. Producers only devoted a small proportion of their land to these activities. These results differ from those of Sckokai and Moro (2006), who confirmed their hypothesis of risk-averse behavior for all types of farms. A possible explanation may be the unit of analysis; producers may be risk-averse overall, but may not show risk-averse behavior for all activities.

Second, changes between land uses depend on whether production activities are complements or substitutes. For dairy farming, fodder maize and grassland appear to be complements. For arable farming, cereals, sugar beets, and potatoes appear to be complements, whereas onions and grassland appears to be a substitute. This is consistent with Philippidis and Hubbard (2003) who find a change from oilseeds to cereals and a change from cattle to milk under the Agenda 2000 reform. Vegetables isare not cultivated in rotation systems with other crops, which is reflected by the low response in relation to other land uses.

The complements within dairy farming and the complements and substitutes within arable farming may indicate competition within both categories of land use, and separation between them. A producer may view alternative production decisions only within the context of either arable farming or dairy farming depending on their current production activities. Switches between arable and dairy farming would involve higher transaction costs. This difference may also result from the perceived difficulty of converting grassland into other land uses due to soil conditions. Further research, splitting the land between arable and dairy sectors is necessary to test to what extent this hypothesis holds.

There are several caveats related to our approach. Data limitations did not allow us to disaggregate yields to the regional level. Because the regions had largely homogeneous soil types within a region but heterogeneous soil types between regions, disaggregating yields to the regional level could lead to more accurate estimates. Moreover, although we divided the Netherlands into regions based on homogeneity of soil type, we did not account for the effect of soil type on cultivation decisions. Since some soils may be unsuitable for some crops, a more precise version of our model would account for this. The increase in risk due to output price volatility may be partly offset by risk-reducing direct payments from the government (Ridier and Jacquet, 2002; Sckokai and Moro, 2006) and insurance measures such as forward contracts (Santos, 2002), which we did not account for in our analysis. By including a dummy trend for the introduction of single farm payments, we tried to account for changes in CAP policies. However, other policies, such as production restrictions (quotas) or environmental regulations, may lead to distortions in analyzing the effects of risk.

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Appendix: Derivation from profit function to land use shares

Profit-maximizing producer

Assume a producer who takes the prices of inputs and outputs as exogenous. We define a profit function with multiple outputs (land uses or crops) that treats the total land area as a fixed allocable input:

$$\pi_{ht}(\mathbf{p}_t, \mathbf{w}_t, \mathbf{z}_{ht}, N_{ht}) \equiv \max_{n_{hit}} \sum_i \pi_{hit}(p_{it}, \mathbf{w}_t, \mathbf{z}_{ht}, n_{hit}) \quad h=1,\ldots,H;\ i=1,\ldots,I;\ t=1,\ldots,T^2 \tag{1}$$

Subject to:

$$\sum_i n_{hit} = N_{ht} \tag{2}$$

where $\pi_{ht}(\mathbf{p}_t, \mathbf{w}_t, \mathbf{v}_{ht}, N_{ht})$ represents the total profit for producer h in year t; $\mathbf{p}_t$ represents the vector of exogenous output prices in year t; $\mathbf{w}_t$ represents the vector of exogenous variable input prices in year t; $\mathbf{z}_{ht}$ represents the vector of quantities of fixed inputs for producer h in year t; N_{ht} represents the total number of hectares to be allocated to different land uses by producer h in year t; $\pi_{hit}(\mathbf{p}_{it}, \mathbf{z}_{ht}, n_{hit})$ represents the profit for a producer of land use i in year t; p_{it} represents the output price of land use i in year t; n_{hit} represents the number of hectares for producer h allocated to land use i in year t.

Exogenous output prices (p_{it}) differ among land uses and years, whereas exogenous input prices ($\mathbf{w}_t$) are the same for all land uses. The use of variable inputs differs among land uses. However, although the amount of fixed inputs differs among producers and years we make the restrictive assumption that land use depends on the total amount of fixed inputs on a farm. So, fixed inputs are not allocated to individual land uses. In this article, we will assume that there is no variation in soil type within regions. However, there is variation between regions as regions are divided on the basis of soil type. The total land area available to all producers is $N_t = \sum_h \sum_i n_{hit}$, which equals the total amount of agricultural land available in a specific year.

Assuming that output in terms of quantity of a crop (land use) is the product of a fixed exogenous yield per hectare () and the number of hectares, equation 1 can be written as:

$$\pi_{ht}(\mathbf{p}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht}) \equiv \max_{n_{hit}} \sum_i \left\{ p_{it} \cdot q_{hit} . n_{hit} - \mathrm{C}(\mathbf{w}_t, n_{hit}, q_{hit}, \mathbf{z}_{ht}) \right\} \tag{3}$$

$$\sum_i n_{hit} = N_{ht} \tag{4}$$

Where $\mathbf{q}_{ht}$ is the vector of different crop yields for producer h in year t.

Because producers do not know the price for a given product at the time they make their production decisions, we must deal with *expected* output prices instead of *observed* output prices. Input prices are typically known at the time of purchase, and therefore producers do not let their land-use decisions be determined by their expectations on the variability of input prices (Chavas and Holt, 1990). Thus, equation 3 can be rewritten as:

$$\mathrm{E}\pi_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht}) \equiv \max_{n_{hit}} \sum_i \left\{ \hat{p}_{it} \cdot q_{hit} . n_{hit} - \mathrm{C}(\mathbf{w}_t, n_{hit}, q_{hit}, \mathbf{z}_{ht}) \right\} \tag{5}$$

where $\mathrm{E}\pi_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht})$ represents the expected profit for producer h in year t, and represents the vector for the expected output prices.

Utility-maximizing producers

Expected utility is determined by the expected profit defined in equation 5, the variance of profit, and the coefficients of absolute risk aversion per crop. The utility function (U_{ht}) can be denoted by the following equation (see e.g. Coyle, 1992):

$$\mathrm{U}_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht}, \mathrm{V}\pi_{\mathrm{ht}}) = \mathrm{E}\pi_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht}) - 0.5\boldsymbol{\alpha}_h\ \mathrm{V}\pi_{\mathrm{ht}} \tag{6}$$

Where $U_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, N_{ht}, \mathrm{V}\pi_{\mathrm{ht}})$ represents the indirect utility for producer h in year t; $\mathrm{V}\pi_{\mathrm{ht}}$ represents the vector of variance of profit for producer h and year t; and $\boldsymbol{\alpha}_h$ represents a vector of coefficients of absolute risk aversion for the different outputs for producer h.

Following the method of Coyle (1992), we assumed that the variance of profit is given by:

$$\mathrm{V}\pi_{\mathrm{ht}} = \mathbf{n}_{ht} \cdot \mathbf{Vp} \cdot \mathbf{n}_{ht}^{\mathrm{T}} \tag{7}$$

where $\mathbf{Vp}$ represents the symmetric, positive, definite covariance matrix of output prices. $\mathbf{n}_{\mathbf{ht}}$ represents the vector of the number of hectares allocated to the different land uses for producer h in year t, $\mathbf{n}^{\mathrm{T}}_{ht}$ represents the transpose of $\mathbf{n}_{ht}$.

If we substitute the expected value of the profits (Eq. 5) and the expected variance of the profits (Eq. 7) into the expected utility function (Eq. 6), we obtain the following indirect utility function:

$$\mathrm{U}_{ht}(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, \mathbf{Vp}, N_{ht}) = \max_{n_{hit}} \mathrm{U}_{ht}\Big(\hat{\mathbf{p}}_t \cdot \mathbf{q}_{ht} . \mathbf{n}_{ht} - \mathrm{C}(\mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{n}_{ht}, \mathbf{z}_{ht}) - 0.5\boldsymbol{\alpha}_h \mathbf{n}_{ht}^{\mathrm{T}} \cdot \mathbf{Vp} \cdot \mathbf{n}_{ht}\Big) \quad n_i \in \mathrm{T} \tag{8}$$

The indirect utility function represents the relationship between the maximum attainable utility (max U) and the exogenous variables $\hat{\mathbf{p}}_t$, $\mathbf{w}_t$, $\mathbf{q}_{ht}$, $\mathbf{z}_{ht}$, $\mathbf{Vp}$, and N_{ht} (Oude Lansink, 1999). This utility function has the following properties: increasing in expected output prices and yields, decreasing in variable input prices, decreasing in the variance of output prices, linear homogenous and convex in output prices, input prices and the variance of output prices (Coyle, 1990).

The variable of absolute risk aversion α_{hi} is measured per producer and per crop. For any value of $\alpha_{hi} > 0$, the producer is risk-averse (Chavas and Pope, 1982). In the case of

[2] For reasons of simplicity we discard the specification for *h, i,* and *t* from further equations.

a risk-neutral producer (α_{hi}=0), the term that captures the risky environment, which equals the risk coefficient multiplied by the variance of profit ($0.5\alpha_{hi}$) disappears from the equation.

The Lagrangian for the indirect utility function (Eq. 8), denoted L^U_{ht}, equals:

$$L^{U}_{ht} = \left(\hat{\mathbf{p}}_t \cdot \mathbf{q}_{ht} . \mathbf{n}_{ht} - C\left(\mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{n}_{ht}, \mathbf{z}_{ht}\right) - 0.5\boldsymbol{\alpha}_h \mathbf{n}^{T}_{ht} \cdot \mathbf{Vp} \cdot \mathbf{n}_{ht} + \lambda_{ht}\left(N_{ht} - \mathbf{n}_{ht}\right)\right) \quad (9)$$

where λ_{ht} represents the shadow price of the land constraint. The necessary first-order conditions for an interior solution are:

$$\frac{\partial L^{U}_{ht}}{\partial \mathbf{n}_{ht}} = \hat{\mathbf{p}}_t . \mathbf{q}_{ht} - C'\left(\mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{n}_{ht}, \mathbf{z}_{ht}\right) = \boldsymbol{\alpha}_h \cdot \mathbf{Vp} \cdot \mathbf{n}_{ht} - \lambda_{ht} \quad (10)$$

$$N_{ht} - \mathbf{n}_{ht} = 0 \quad (11)$$

Equation 10 allocates the available land among land uses based on the marginal utility from each land use. The input constraint in Eq. 11 is binding if we require an interior solution. Solving equations 10 and 11 gives the optimal allocation of land use i for producer h in year t[3]:

$$\mathbf{n}^{U}_{ht} = \left(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, \mathbf{Vp}, N_{ht}\right) \quad (12)$$

Land-use Share Equations

Now, let us assume that the optimal allocation of land ($\mathbf{n}^U_{ht}$) is homogeneous of degree 1 in N_{ht}[4]. For the utility-maximizing producer, we then get:

$$\mathbf{n}^{U}_{ht}\left(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, \mathbf{Vp}, N_{ht}\right) = \mathbf{n}^{U}_{ht}\left(\hat{\mathbf{p}}_t, \mathbf{w}_t, \mathbf{q}_{ht}, \mathbf{z}_{ht}, \mathbf{Vp}, 1\right) N_{ht} \quad (13)$$

This means that if the total amount of land decreases with the factor b, the amount of land allocated to land use i also decreases with the factor b. Equation 13 can be rewritten towards a land-use share function (see equation 1 in the main text).

[3] Note that upon solving equation 12 the variable of absolute risk aversion αhi drops from the equation.

[4] Homogeneity of degree 1 in land is a necessary assumption to specify the model in land use shares because this implies that any added land will be split up exactly among crops.