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Abstract

Crop rotations are an important factor for the design and implementation of sustainable agricultural systems. Integrated agricultural land use models increasingly acknowledge the role of crop rotations by assessing economic and environmental impacts of agricultural production systems. However, insufficient data on crop rotations often challenge their implementation. In this article, we present the crop rotation optimization model CropRota. CropRota integrates agronomic criteria and historical crop mixes at field, farm, or regional scales in order to generate optimal crop rotations for the particular scale. The article describes model structure, empirical crop mix data, and its application and validation for a case study region in Austria. Model calibration and sensitivity analysis are conducted to emphasize the importance of sound expert judgments on assumptions about crop rotations. The comparison of model results against seven years of field survey data from 579 farms in the Mostviertel region of Austria indicates that CropRota is suitable and reliable in modeling typical crop rotations. A model approach based on calibrated model parameters delivered weighted deviations of modeled and observed crop sequences of around 10% for the most important two-crop sequences covering 50% of total crop lands in the region.

Key words

crop rotation; crop sequence; modeling; optimization; sustainable agricultural systems

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1 Introduction

Crop rotations as defining feature of any cropping system are an important factor for the design and implementation of sustainable agricultural systems (Ball *et al.*, 2005). They affect the quality of the abiotic and biotic environment, e.g. by influencing nitrogen content in water bodies (Broussard and Turner, 2009) or levels of biodiversity in agricultural landscapes (Kleijn and Verbeek, 2000; Robinson and Sutherland, 2002). Crop rotations also determine the appearance of agricultural landscapes by influencing its diversity, which is an important factor concerning the aesthetic value of cultural landscapes (Hendriks *et al.*, 2000). Besides these non-market impacts of crop rotations are net revenue effects, labor organizational efforts, and risk management among socio-economic impacts. Complex crop rotations can be used to manage risks by diversifying production and costs as well as by hedging commodity prices (Di Falco and Perrings, 2005). Crop rotations can also influence the level of natural resource utilization, e.g. by determining the availability of nitrogen and water in the soil (Smith *et al.*, 2008), or the occurrence of pests and diseases (Tilman *et al.*, 2002). However, an increasing diversity of crops may reduce economies of scale and, hence, may decrease farm net revenues and increase labor organizational efforts.

Complex rotations with high crop diversity from different plant families are usually considered beneficial for the environment, landscape aesthetics, and the sustainability of agricultural systems, i.e. they deliver public benefits. However, farmers' decisions on crop rotations are often based on private benefits and costs (Cutforth *et al.*, 2001; Vavra and Colman, 2003). This divergence between private costs and public benefits may explain the reduction of complex crop rotations since the agricultural industrialization (Souchère *et al.*, 2003; Dogliotti *et al.*, 2006), as simple crop rotations with high cash crop shares are often employed to maximize short-term farm profits. Agri-environmental programs seek to take this divergence of public and private costs and benefits into account by offering payments to farmers who comply with certain crop rotation standards.

Integrated agricultural land use modeling increasingly acknowledges the role of crop rotations in adequately assessing the combined economic and environmental impacts of agricultural production systems. Crop rotations represent perpetual crop series on a piece of land, while crop sequences are consecutive series of crops (Leteinturier *et al.*, 2006) that can but need not to be part of a crop rotation. The utilization of crop rotations instead of mere crop sequences that express e.g. pre-crop – main crop relationships, allows more generalized interpretation of land use model results. The analysis of new agri-environmental programs offering crop rotation measures may require such explicit representations as well. Bio-physical process models like EPIC (Williams, 1995) or CropSyst (Bechini and Stöckle, 2007) rely on crop rotation input data for generating output on crop yields and environmental impacts of agricultural production systems. Economic land use models, especially bottom-up models employing mathematical programming methods, use crop rotation constraints to properly reflect the mutual impacts of crops on crop yields, production costs, and endowments of land, labor, and machinery. They may range from constraints on the share of crops on farms or in regions (e.g. Mosnier *et al.*, 2009) up to the explicit implementation of crop rotations (e.g. Dogliotti *et al.*, 2006). The latter are more likely to be found in farm models than in regional or sector models. For example, Janssen and van Ittersum (2007) review 48 bio-economic farm model studies and find crop rotation constraints in 27 studies. A major obstacle to the implementation in mathematical models is the availability of empirical farm data on current or historical crop rotations. Available information usually includes total annual crop areas aggregated over an unknown number of rotations. Individual crop rotations cannot be directly derived from such data so far.

To address this data deficiency, several methodological approaches, either empirical investigations or mathematical models, have been developed. Some of them are discussed in Castellazzi et al. (2008). Approaches range from inter-temporal landscape surveys to interviews of farmers and experts on practically applied crop rotations (Mignolet *et al.*, 2004; Colbach *et al.*, 2005). The software tool ROTAT (Dogliotti *et al.*, 2006), for example, has been developed to provide all possible combinations from a given set of crops and according to agronomic criteria. Similarly, the rule-based model ROTOR (Bachinger and Zander, 2007) generates agronomically sustainable crop rotations taking into account plant nutrition, weed infestation and phyto-sanitary effects. Detlefsen and Jensen (2007) apply a network flow model to find optimal rotations by maximizing the gross margins for each sequence of crops. Constraints in their approach are the shares of crops to be modeled in the year of interest. El-Nazer and McCarl (1986) develop a procedure for the identification of optimal long-run crop rotations to be integrated into linear programming models. They derived empirical data on the economic effects of crop sequences from regression analysis. While the first two examples only consider agronomic criteria in delineating crop rotations, the latter ones generate optimized rotations based on gross margins. Even in cases where empirical data on consecutive crop sequences on a field basis are available, such crop rotation models may be still useful to find crop rotations in a more generalized form. However, several research questions remain in crop rotation modeling such as how to reduce the sometimes large number of potentially available crop rotations to realistic ones for the region, and how to validate these?

In this article, we combine agronomic and economic criteria to develop a crop rotation optimization model, hereafter named CropRota. CropRota integrates agronomic rules and historical crop mixes either at field, farm, or regional scales in order to generate optimal crop rotations. A major difference of CropRota to many existing crop rotation models is its capability to weigh the importance of generated crop rotations according to observed crop mixes. In addition, substantial efforts are put into model validation and calibration. The article is organized as follows. In Chapter 2, we describe the model structure of CropRota, its data requirements and underlying assumptions, and more specifically the case study application for 579 farms in the Mostviertel region of Austria. Chapter 3 presents basic case study model results and validates them against seven years of field survey data. Model calibration and sensitivity analysis show the importance of sound expert judgments on assumptions about crop rotations. Chapter 4 discusses the quality of our results. We finish our article by suggesting further model improvements and interesting model applications (Chapter 5).

2 Methods and data

2.1 Model structure and data requirements

CropRota is a linear optimization model that derives agronomically optimal crop rotations and their distribution from observed land use data (Figure 1). The model uses data on relative crop shares $S_{\dot{c}}$, i.e. crop mixes for a farm, region, or any other spatial unit of a certain time period such as a year or an average of several years. The set of crops *C* currently represented in CropRota entails 42 crops.

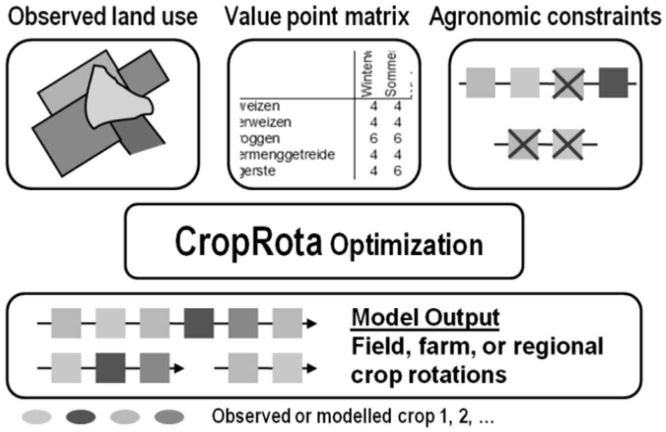


Figure 1: CropRota model structure

Crop rotations are repeating sequences of succeeding crops ($\dot{c}, \ddot{c}, \dddot{c}, \dots, c^{n}$) on a land unit, where $\dot{c}, \ddot{c}, \dddot{c}, \dots, c^{n}$ represent subsets of *C*. In CropRota, the decision variables $R^1_{\dot{c},}$, $R^2_{\dot{c},\ddot{c}}, \dots, R^n_{\dot{c},\dots,n}$ represent the shares as well as sequence and number of crops in the rotations, which are part of the set of observed crops *B*. For instance, $R^1_{\dot{c}}$ refers to a monoculture whereas $R^3_{\dot{c},\ddot{c},\dddot{c}}$ refers to a crop rotation with three crops in sequence. In the current version of CropRota, we limit the maximum number of crops in a rotation to six, i.e. $R^6_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\ddddot{c},\ddddot{c}}$. CropRota maximizes the total agronomical value (*TotValue*) of crop sequences in the rotations. These crop sequences are usually described in crop rotation tables (in German: ‘Fruchtfolgekreuz’, Appendix 1), which are frequently applied tools guiding crop planting decisions of farmers and farming consultants (Andreae, 1959; Freyer, 2003). Experts valued the crop sequences, which we have converted into a point-value matrix ($p_{\dot{c},\ddot{c}}$)

ranging from zero points (agronomically impossible sequence) to ten points (agronomically highly desirable sequence). The objective function (2.1) is described as follows:

$$max.TotValue =$$

$$\frac{1}{2}\sum_{\dot{c}}[p_{\dot{c},\dot{c}}\ R^1_{\dot{c}}] + \sum_{\dot{c},\ddot{c}}[\frac{1}{2}\ p_{\dot{c},\ddot{c}}\ (R^2_{\dot{c},\ddot{c}} + R^2_{\ddot{c},\dot{c}})] + \sum_{\dot{c},\ddot{c},\dddot{c}}[\frac{1}{3}\ p_{\dot{c},\ddot{c}}\ (R^3_{\dot{c},\ddot{c},\dddot{c}} + R^3_{\ddot{c},\dddot{c},\dot{c}} + R^3_{\dddot{c},\dot{c},\ddot{c}})]$$

$$+ \sum_{\dot{c},\ddot{c},\dddot{c},\ddddot{c}}[\frac{1}{4}\ p_{\dot{c},\ddot{c}}\ (R^4_{\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^4_{\ddot{c},\dddot{c},\ddddot{c},\dot{c}} + R^4_{\dddot{c},\ddddot{c},\dot{c},\ddot{c}} + R^4_{\ddddot{c},\dot{c},\ddot{c},\dddot{c}})]$$

$$+ \sum_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}}[\frac{1}{5}\ p_{\dot{c},\ddot{c}}\ (R^5_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}} + R^5_{\overset{.....}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^5_{\ddddot{c},\overset{.....}{c},\dot{c},\ddot{c},\dddot{c}} + R^5_{\dddot{c},\ddddot{c},\overset{.....}{c},\dot{c},\ddot{c}} + R^5_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\dot{c}})]$$

$$+ \sum_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}}[\frac{1}{6}\ p_{\dot{c},\ddot{c}}\ (R^6_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}} + R^6_{\overset{......}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}} + R^6_{\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^6_{\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c},\dddot{c}} + R^6_{\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c}} + R^6_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c}})]$$

$$- \sum_{\dot{c}}[(T_{\dot{c}} + U_{\dot{c}}) * d] \qquad (2.1)$$

The decision variables $R^n_{\dot{c},\ldots,n}$ are arranged such that the total value of all crop sequences in a rotation is maximized. The crop rotational values for each crop rotation are normalized by its number of crop sequences (e.g. 1/6 for $R^6_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}}$). According to expert judgments, the point-values for monocultures are reduced by 50% to taking into account their disadvantageous agronomic effects in the long run. $T_{\dot{c}}$ and $U_{\dot{c}}$ are slack variables to avoid infeasibilities in multiple model runs and are penalized by *d*. The decision variables are restricted by the following block of constraints (2.2) to match the observed crop share $S_{\dot{c}}$.

$$R^1_{\dot{c}} + \sum_{\ddot{c}}[\frac{1}{2}(R^2_{\dot{c},\ddot{c}} + R^2_{\ddot{c},\dot{c}})] + \sum_{\ddot{c},\dddot{c}}[\frac{1}{3}(R^3_{\dot{c},\ddot{c},\dddot{c}} + R^3_{\dddot{c},\dot{c},\ddot{c}} + R^3_{\ddot{c},\dddot{c},\dot{c}})]$$

$$+ \sum_{\ddot{c},\dddot{c},\ddddot{c}}[\frac{1}{4}(R^4_{\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^4_{\ddddot{c},\dot{c},\ddot{c},\dddot{c}} + R^4_{\dddot{c},\ddddot{c},\dot{c},\ddot{c}} + R^4_{\ddot{c},\dddot{c},\ddddot{c},\dot{c}})]$$

$$+ \sum_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}}[\frac{1}{5}(R^5_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}} + R^5_{\overset{.....}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^5_{\ddddot{c},\overset{.....}{c},\dot{c},\ddot{c},\dddot{c}} + R^5_{\dddot{c},\ddddot{c},\overset{.....}{c},\dot{c},\ddot{c}} + R^5_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\dot{c}})]$$

$$+ \sum_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}}[\frac{1}{6}(R^6_{\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}} + R^6_{\overset{......}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c}} + R^6_{\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c},\dddot{c},\ddddot{c}} + R^6_{\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c},\dddot{c}} + R^6_{\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c},\ddot{c}} + R^6_{\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c},\dot{c}})]$$

$$- T_{\dot{c}} + U_{\dot{c}} \ = \ S_{\dot{c}} \qquad \forall\ \dot{c} \in B\ , where\ (\ddot{c},\dddot{c},\ddddot{c},\overset{.....}{c},\overset{......}{c}) \in B \qquad (2.2)$$

Additional constraints limit the frequency of one and the same crop in a crop rotation according to expert judgments (Table 1).

Table 1: Parameters for CropRota constraints

object of constraint	*constraint type*	*value*
peas	frequency	max.1 in 4 yrs.
field beans	frequency	max.1 in 4 yrs.
peas and field beans	frequency	max.1 in 4 yrs.
sunflower	frequency	max.1 in 4 yrs.
rape seed	frequency	max.1 in 5 yrs.
sugar beet	frequency	max.1 in 4 yrs.
rapeseed and sugar beet	frequency	max.1 in 3 yrs.
potatoes	frequency	max.1 in 4 yrs.
red clover	frequency	max. 1 in 3 yrs.
red clover, alfalfa, red clover grass, and temp. grass	frequency	max. 3 in rotations > 3 yrs.[1)]
red clover, alfalfa, red clover grass, and temp. grass	rotation length	min. 4 yrs. [1)]
red clover grass and temporary grass	rotation length	min. 2 yrs. [2)]

[1)] for crop mixes > 2 crops
[2)] for crop mixes > 1 crop

With additional constraints one may prevent monoculture-like combinations, e.g. a six-crop rotation with only two different crops. CropRota is written in GAMS-software comprising a loop statement to run over a set of alternative crop mixes.

2.2 Case study data

Data are from the case study region ‘Mostviertel’, which is part of the federal province Lower Austria consisting of the districts Amstetten, Melk, Scheibbs, and Waidhofen/Ybbs. The ‘Mostviertel’ region is characterized by a high diversity in land uses, farm structures, and landscapes. There are larger, intensive crop and livestock farms in the relatively flat North and smaller, extensive grassland farms in the alpine South.

Farm and field land use data are derived from the IACS data base (BMLFUW, 2008), which was introduced in 1995 in order to administer EU and national agricultural subsidies in Austria. Most of the subsidy schemes for Austrian farmers are related to land, which requires the registration of all fields managed by a farmer. The land use data on field scale represent more than 90% of all agricultural land in Austria and a share of 5% is annually monitored (personal communication, AMA, 5.3.2008). Among others, field size, land use, and management data are available for the period 2001 to 2007.

One aim of this analysis is to validate CropRota results against empirical field observations at the farm level. For the regional case study, we selected only farms from the IACS data base, which kept their number and indications of those fields we can observe in 2001 unchanged until 2007. In order to reduce the risk of misleading crop sequences due to changing sub-fields, farms with field size variations of more than 20% from 2001 onwards have been excluded as well. IACS covers about 350 different crop types. We aggregated the observed 117 different entries of our case study region to 34 that are currently represented in CropRota. In particular, we combined crop types with similar cultivation techniques and agronomic effects. For example, winter wheat for feed or human nutrition was aggregated to winter wheat.

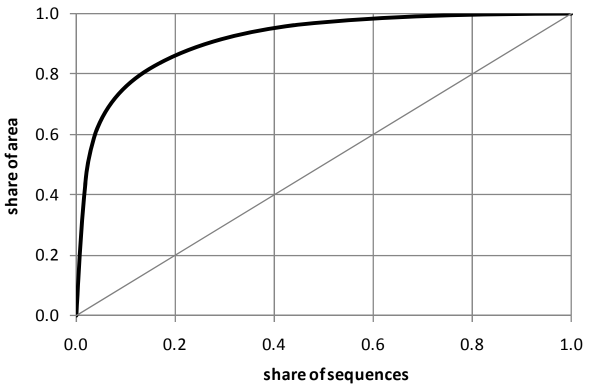


Figure 3: Distribution of observed two-crop sequences from 2001 to 2007

For some crop mixes, CropRota does not represent the farm area exactly or does not generate rotations at all due to the use of slack variables. The latter can be the case especially for annual input data of small farms consisting of self-intolerant crops (e.g. peas or sugar beets). Therefore, we proportionally corrected the sum of relative shares of resulted crop rotations on a farm to a total of 100%.

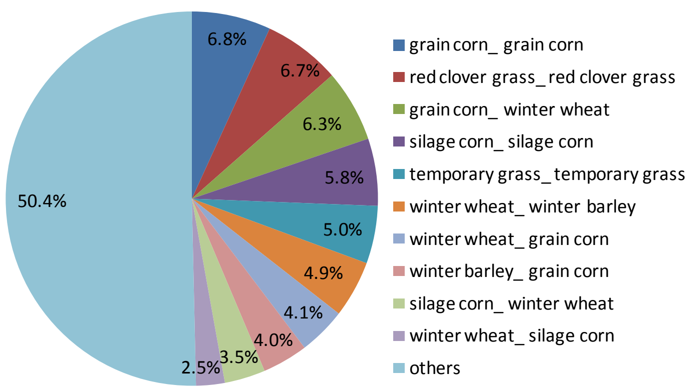


Figure 4: Share of observed top ten two-crop sequences for the total crop land from 2001 to 2007

In 2001, 9,153 farms were recorded in IACS of which 6,445 farms cultivated crops in the case study region. Only 579 farms with 2,008 fields and an area of 2,048.9 ha meet both criteria, consistency in field number and field size between 2001 and 2007. The annual crop data from 2001 to 2007 result in six two-crop sequences to be observed, which sextuples the total observed field area to 12,293.4 ha. The 34 different crops theoretically lead to 1,156 (= 34^2) two-crop sequences and 39,304 (= 34^3) three-crop sequences. However, the actual crop combinations are 443 two-crop and 1,698 three-crop sequences.

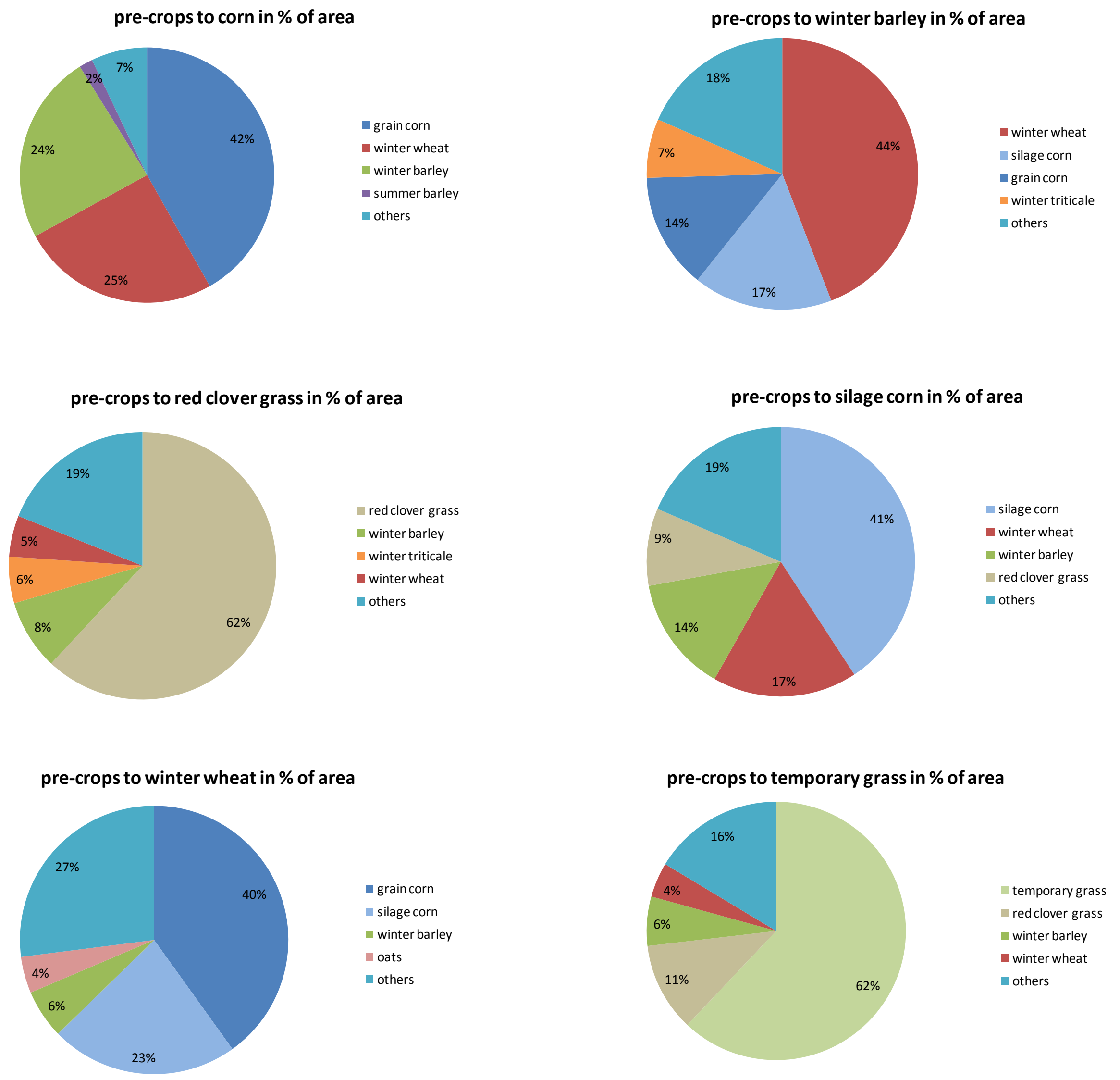


Figure 5: Distribution of observed pre-crops for the most important main crops from 2001 to 2007

The concentration in the distribution of sequences is shown in Figure 3. For example, the ten most important two-crop sequences - presented in Figure 4 - have a cumulative share of

50% on total crop lands, the 30 most important two-crop sequences amount to a share of 70%. Figure 5 shows the distribution of alternative pre-crops to a specific main crop. The six main crops cover 76% of observed crop lands and are part of 140 out of the 443 different two-crop sequences.

3. Results

3.1 CropRota case study results

Historically observed crop mix data can enter CropRota as time series or annual average. In model approach A, one average crop mix for each farm was calculated for the years 2001 to 2007. Hence, CropRota generates only one set of crop rotations per farm. In model approach B, one set of crop rotations for each of the seven years is modeled based on annual farm crop mixes.

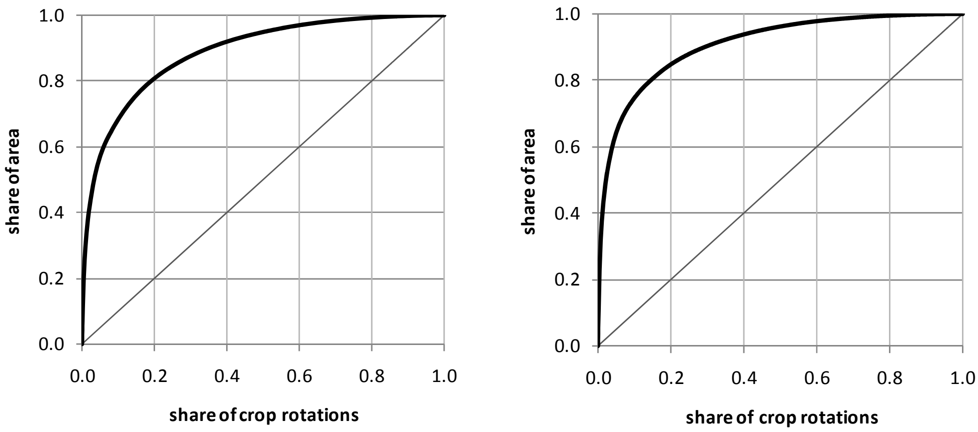


Figure 6: Distribution of crop rotations of model approaches A (left) and B (right)

Approach A results in 858 unique crop rotations covering total crop lands of 2,039 ha on 570 farms. For nine farms, CropRota does not find any solution. Their crop mixes contain too large shares of self-intolerant crops. In total, 29 or 3.4% of all modeled crop rotations account for more than 50% of total crop lands (Table 2, Figure 6). The 50% most important crop rotations of approach B with respect to crop land area are presented in Table 3.

Table 2: Top 29 crop rotations of model approach A covering 50% of the modeled area

year 1	year 2	year 3	year 4	year 5	year 6	area (ha)	% of all crop rotations
silage corn	winter wheat					114	5.6
winter wheat	grain corn					108	5.3
grain corn	winter wheat	winter barley	grain corn	grain corn	grain corn	87	4.3
winter wheat	winter barley	grain corn				86	4.2
winter wheat	grain corn	grain corn	grain corn	grain corn	grain corn	59	2.9
silage corn	winter barley					58	2.8
grain corn						43	2.1
temporary grass	temporary grass	silage corn	temporary grass	temporary grass	temporary grass	36	1.8
winter barley	silage corn	silage corn	red clover grass	red clover grass	red clover grass	36	1.8
temporary grass						33	1.6
winter triticale	winter barley					28	1.4
red clover grass	red clover grass	silage corn	silage corn	silage corn	red clover grass	28	1.4
temporary grass	temporary grass	temporary grass	temporary grass	winter barley	temporary grass	28	1.4
winter wheat	pumpkin					25	1.2
silage corn						24	1.2
CCM						21	1.1
red clover grass	silage corn	winter wheat	silage corn	red clover grass	red clover grass	20	1.0
silage corn	winter triticale					18	0.9
winter wheat	winter barley	silage corn				17	0.8
winter barley	oats	winter wheat				16	0.8
silage corn	red clover grass	red clover grass	red clover grass	winter triticale	silage corn	16	0.8
silage corn	silage corn	silage corn	winter wheat	silage corn	silage corn	16	0.8
winter barley	red clover grass	red clover grass	red clover grass	winter barley	silage corn	16	0.8
rapeseed	winter barley	grain corn	winter wheat	grain corn	winter wheat	16	0.8
temporary grass	winter triticale	temporary grass	temporary grass	temporary grass	temporary grass	15	0.8
winter wheat	sugar beet	winter wheat	grain corn	grain corn		15	0.7
grain corn	grain corn	oats	winter barley	grain corn	grain corn	15	0.7
oats	winter wheat					14	0.7
winter barley						13	0.6

In order to allow comparison between both approaches, we normalize the results from B by dividing the total area by seven. Consequently, approach B results in 1,088 unique crop rotations on 1,978 ha crop lands. CropRota finds optimal solutions for 3,736 out of 4,053 farm and year combinations. The concentration in the distribution of crop rotations is even higher than in approach A by only 24 (= 2.2%) crop rotations accounting for 50% of all crop lands (Figure 6). Both model approaches show similar results with respect to the most important crop rotations. Among them, there are nine crop rotations in approach A, which are missing in B and four in approach B that are missing in A. The higher number of both, farms without solutions and monocultures in model approach B are the result of less diverse annual crop mixes with higher shares of self-intolerant crops in comparison to multi-year average crop mixes.

Table 3: Top 24 crop rotations of model approach B covering 50% of the modeled area

year 1	year 2	year 3	year 4	year 5	year 6	area (ha)	% of all crop rotations
grain corn						140	7.1
winter wheat	grain corn					97	4.9
temporary grass						75	3.8
silage corn	winter wheat					75	3.8
winter barley						61	3.1
winter wheat	winter barley	grain corn				53	2.7
silage corn	winter barley					50	2.5
winter wheat	grain corn	grain corn	grain corn	grain corn	grain corn	47	2.4
red clover grass	red clover grass	silage corn	silage corn	silage corn	red clover grass	45	2.3
silage corn						45	2.3
winter wheat						44	2.2
CCM						26	1.3
temporary grass	temporary grass	silage corn	temporary grass	temporary grass	temporary grass	23	1.2
grain corn	winter wheat	winter barley	grain corn	grain corn	grain corn	23	1.2
winter wheat	winter barley	silage corn				23	1.2
winter barley	silage corn	silage corn	red clover grass	red clover grass	red clover grass	23	1.2
winter wheat	winter barley					22	1.1
silage corn	winter triticale					22	1.1
silage corn	silage corn	silage corn	winter wheat	silage corn	silage corn	19	1.0
winter triticale	winter barley					17	0.9
winter barley	red clover grass	red clover grass	red clover grass	winter barley	silage corn	16	0.8
red clover grass	silage corn	winter wheat	silage corn	red clover grass	red clover grass	15	0.7
winter wheat	peas	winter barley	grain corn			14	0.7
oats						14	0.7

3.2 Model validation

As for many other crop rotation models, the risk of arbitrary and misleading expert knowledge (Dogliotti *et al.*, 2003) is true for CropRota as well. Even if the value point matrix and the constraints on frequencies of certain crops in a crop rotation are well specified by experts, deviations of modeled and observed crop rotations are likely for various reasons. Knowledge about model performance is crucial to any further use of model results and, therefore, we validate the CropRota output by comparing modeled crop sequences to the observed two-crop and three-crop sequences. We apply the concept of deviation, which is defined as the relative difference between observation and model prediction (Mitchell, 1997). Positive and negative deviations of observed and modeled crop sequences are standardized to a positive number before aggregation in order to prevent offsets.

When taking into account those observed crop sequences without any modeled counterpart by a default value of 100%, the weighted average deviation of the modeled two-crop sequences from observed land use is 37% in total. As weight for the comparison, we use the observed area for each two-crop sequence. CropRota generates crop rotations containing those most important observed two-crop sequences that together cover 88% of the land. In total, approach A results in 348 out of 443 observed two-crop sequences. The fit for the most important two-crop sequences with respect to the covered area is much better than for the less important crop sequences. The average weighted deviation is 15% for the top ten crop sequences, which together cover 50% of total crop lands. Only one of these crop sequences is outside a 20% deviation threshold. For the top 30 crop sequences covering 70% of total crop lands, the average weighted deviation is 20%. As expected, the model results deviate more from observed land use data in the case of three-crop sequences, where the total weighted average deviation is 72%. Again, the fit for the most important crop sequences is better with 45% for 50% of total crop lands.

One crop mix for each farm and year is input to CropRota in approach B. The weighted average deviation for all observed two-crop sequences is 49%. For the top ten crop sequences covering 50% of total crop lands, the average weighted deviation is 28% and for the top 30 crop sequences (70% of the land), it is 30%. Similar to approach A, the three-crop sequences deviate more from observed land use data by 82% in total. Again, results for the most important sequences fit better by reaching 50% for both 30% as well as 50% of total crop lands. One conclusion that can be drawn from the scenario results is that an average crop mix delivers more accurate estimates than a set of annual crop mixes.

3.3 Model calibration

Farmers have two major management options for implementing crop rotations (Hazell and Norton, 1986). They may plant the entire farm with one single crop each year. Such strategy allows farmers to exploit economies of scale, but it may also increase production risks due to stochastic crop prices and yields. Furthermore, it may exacerbate seasonal peaks in labor and machinery utilization.

The second major option is to crop a similar mix on a farm each year. If this option is chosen then a multi-year crop mix according to the results of approach A seems more appropriate. This may be also the case for farms with a small number of fields or even only one field but diverse crop rotations. Although such farms may apply a crop rotation on a single field by rotating the crop each year, annual observations will necessarily lead to monocultures in CropRota or even to no solutions at all. The latter may be the case for crops that are prohibited in short rotations monocultures, e.g. peas or sugar beets. Figure 7 shows the distribution of the number of crops on the farms between 2001 and 2007, the number of fields, and the distribution of total arable land per farm. The latter is classified by the following groups: <1, 1-5, 5-10, 10-15, 15-20, 20-25, 25-30,>30 ha/farm. Many farms (27%) in our sample have only one field. As the average number of crops is four for 24% of all observed farms, many farms likely apply a diverse rotation on a relatively small number of fields.

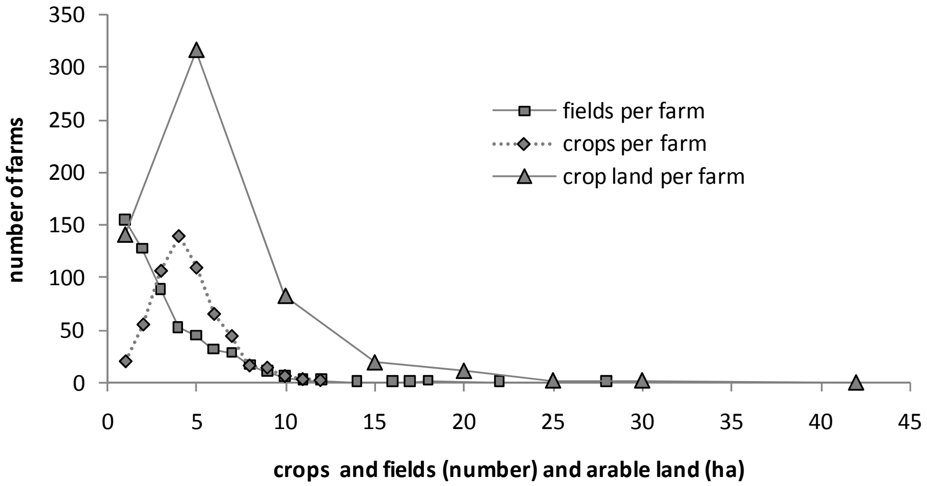


Figure 7: Farm data on the number of crops, fields, and crop land area from 2001 to 2007

We test the hypothesis that average instead of annual crop mixes are more appropriate in such environments by splitting our sample into two sub-samples depending on the number of fields and the sum of crops which were cropped on the farms between 2001 and 2007. There are 185 farms with a field to crop ratio of greater or equal to one, i.e. they had more fields than different crops between 2001 and 2007. 394 farms have a lower field to crop ration than one. These are usually smaller and non-specialized crop farms. The results support the hypothesis that average crop mixes are the more appropriate modeling approach for farms with a low number of fields and a large number of different crops. In any case, the average approach A_394 delivers much better results than approach B_394. The deviations are 51% in B_394 compared to 16% in A_394 for the most important two-crop sequences covering 50% of total observed crop lands. For farms with a higher number of fields than crops, it does not make any large difference whether they are modeled on an annual basis or by applying one average crop mix. However, results may become better with an annual crop mix approach for farms with significantly higher field to crop ratios than one (Schönhart *et al.*, 2009).

Besides optimizing the input data (annual vs. average crop mixes), there are even more options to improve the model performance. Crop rotation models frequently rely on expert judgments. As it has been discussed by Dogliotti et al. (2003), subjectivity or imperfect knowledge may bias results. Recommended practices by experts may deviate from practices that farmers actually apply (Mignolet *et al.*, 2004). For instance, the sequence grain corn-winter barley was judged as agronomically impossible by experts, however, it is still planted on a considerable amount of land in the case study region.

Consequently, we analyze the impact of adjusting the value point matrix on the performance of CropRota. Results of approach A are the starting point for A_1, for which we change the values in the value point matrix for the 30 most important two-crop sequences.

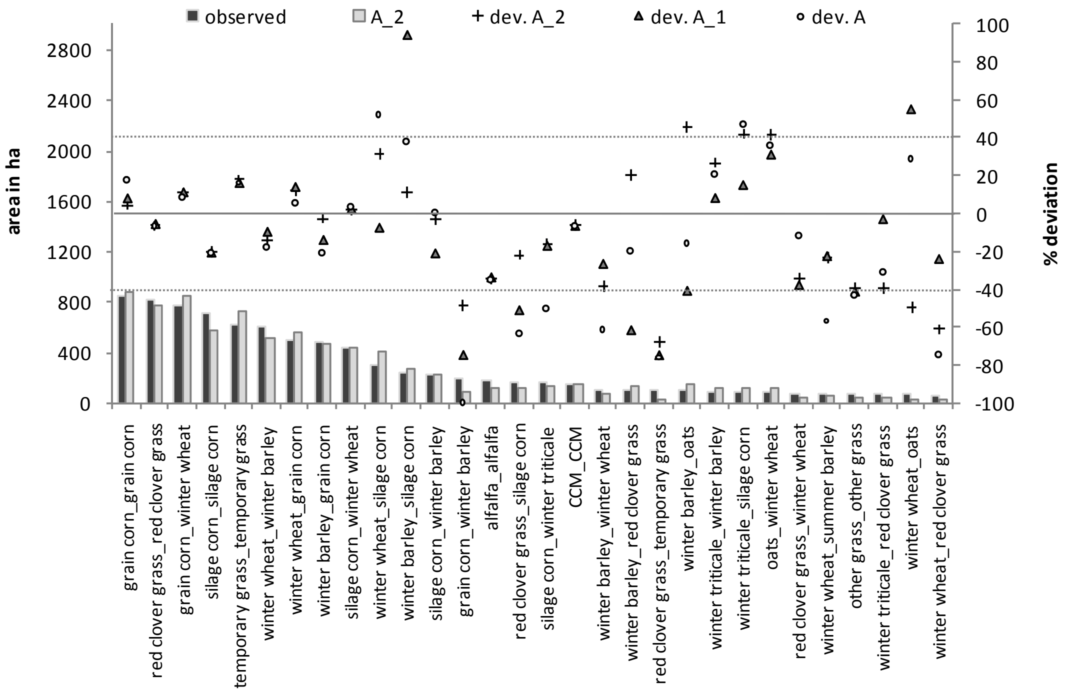
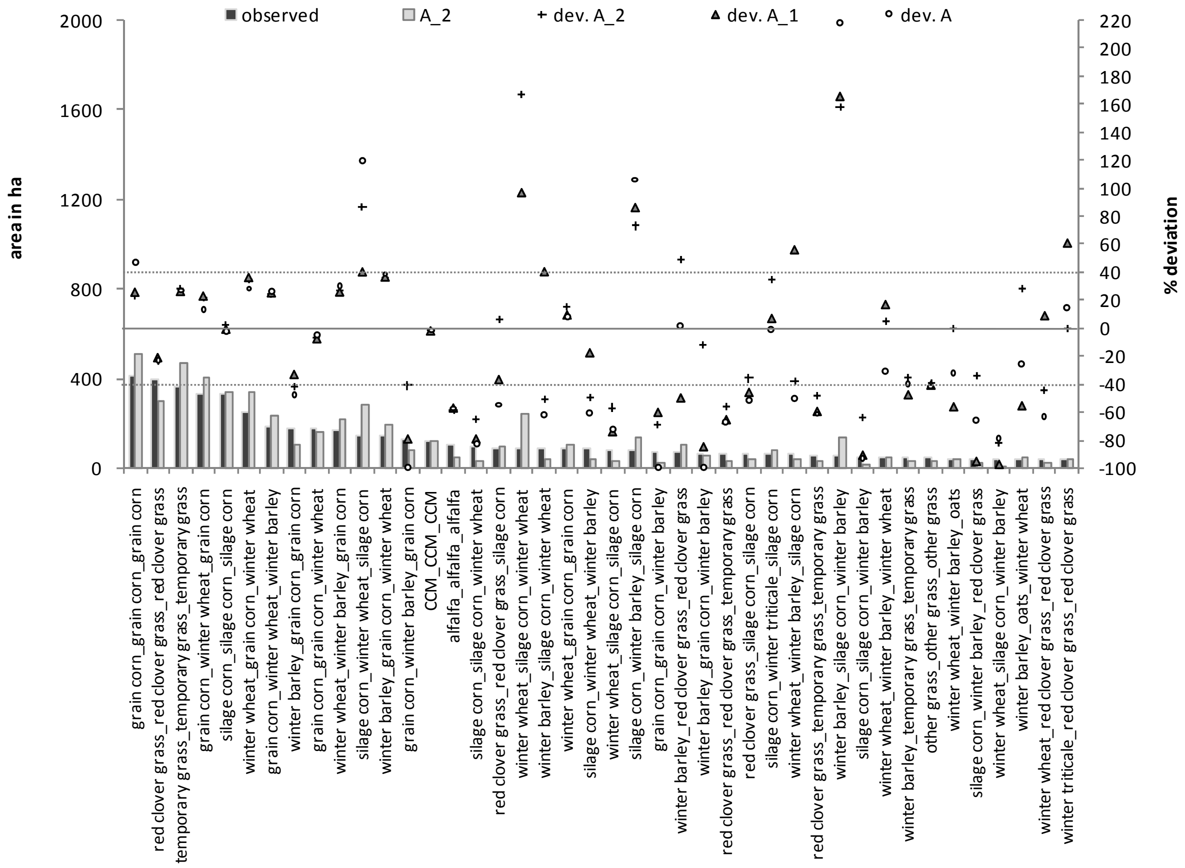


Figure 8: Total area (ha) and deviation (%) of the most important observed and modeled two-crop sequences from the approaches A, A_1, and A_2 covering 70% of the observed total crop land

Deviations of sequences larger than 40% are adjusted by +/- 1 point. Observed sequences with a value of zero in the matrix receive two points. The same procedure is applied a second time for model approach A_2, starting with the results of A_1.



[1] One dot of approach A is outside the graph (winter barley_silage corn_winter barley: 219%).

Figure 9: Total area (ha) and deviation (%) of the most important observed and modeled three-crop sequences from the approaches A, A_1, and A_2 covering 50% of the observed total crop land[1]

Figure 8 and Figure 9 compare the model results of approach A_2 with the observed two- and three-crop sequences. The presented crop sequences cover 70% and 50% of observed crop lands. Results are given in hectares of total crop lands and as relative non-weighted deviations between observed land use data and the model approaches A, A_1, and A_2. For example, grain corn followed by grain corn in Figure 8 is observed on 840 ha, while it is modeled in A_2 on 879 ha. This results in a deviation of + 4%. Winter wheat was planted after grain corn on 770 ha, while it is modeled for 852 ha, i.e. a deviation of 11%. In general, model performance improves with each of the two calibration steps. The weighted total deviations of the two-crop sequences decrease from 36% in A to 35% in A_1 and 33% in

A_2. On the level of three-crop sequences, they are 72%, 66%, and 65% for the approaches A, A_1, and A_2 respectively. As a result of calibration, the deviations of the most important three-crop sequences decrease from 45% in A to 37% in A_1 and 35% in approach A_2. Figure 10 summarizes the average weighted relative deviations for all model approaches and validation levels.

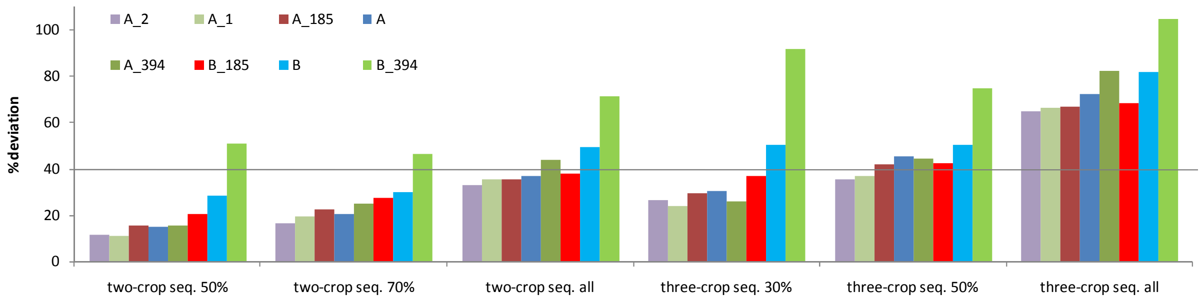


Figure 10: Average weighted deviations (%) for all model approaches and validation levels

The graph compares two- and three-crop sequences according to the area of land covered by these sequences. It shows that the model fit decreases with the number and length of compared crop sequences. Calibration by adapting the value point matrix to region and farm specific circumstances or by adjusting the input data approach (average vs. annual crop mixes) significantly improves model fit. Therefore, we conclude that expert judgments on feasible crop sequences should be validated against observed crop mix data and eventually adapted in order to improve the model performance.

3.4 Sensitivity analysis

The results in chapter 3.3 indicate that model output is sensitive to the specification of the expert-based value point matrix. In order to assess the robustness of the model results, one has to know the variation in model output depending on small variations in the value point matrix specifications. We do such sensitivity analysis by applying Monte Carlo simulation. Using the average crop mix approach A, 200 alternative value point matrices are generated. For each model run, the value point matrix is randomly modified by varying the value of each two-crop sequence by +2, -2, or zero points. We apply a uniform distribution assuming that the likelihood of a point value choice is equal for the proposed range. Modifications above 10 and below 0 are replaced by the starting value 10 or 0. Figure 11 shows several categories of model results for the most important crop sequences, which cover 50% of total crop land.

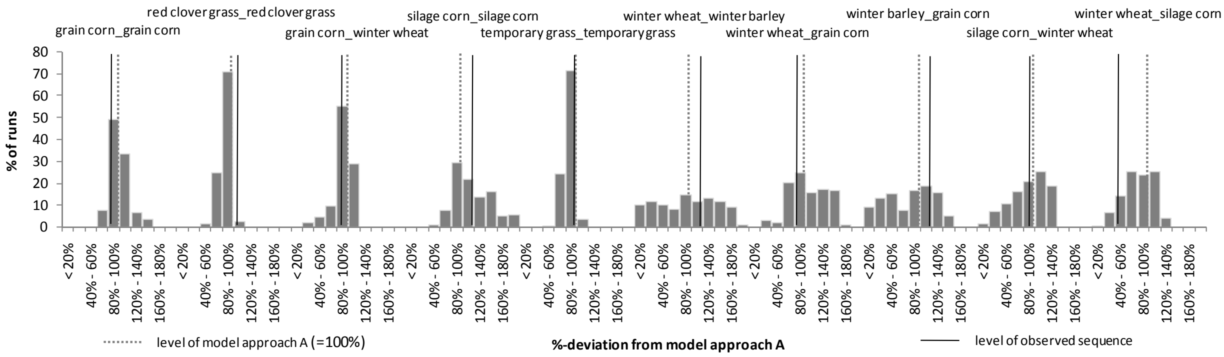


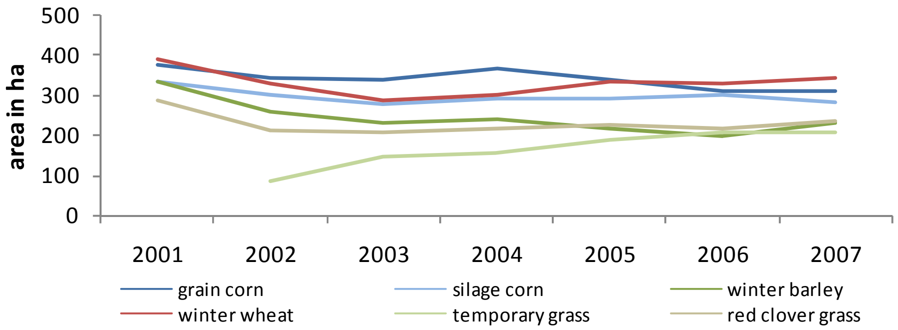
Figure 11: Sensitivity analysis – deviation of model runs with varying value point matrices from observed land use and model approach A

The criterion for categorization is the relative non-weighted deviation of the result from the basic model approach A. For five out of the ten most important crop sequences, more than 50% of the model runs are within a boundary of +/- 20%, and for three crop sequences 40% to 50% of the runs are between these boundaries. Most crop sequences show a distribution close to model approach A (= 100%). Within the presented crop sequences, winter wheat-winter barley shows an almost even distribution of deviations. Crop sequences that are beyond the level of 50% total crop lands show a more diverse picture such that larger deviations from the basic model approach A become more frequent. The results of the sensitivity analysis buttress those of the model calibration, although the latter has been comparably modest by varying points on selected sequences only by +/- 1 point. Both show the sensitiveness of CropRota to the value point matrix, which underlines the importance of expert judgments when designing the value point matrix.

4. Discussion

The performance of the CropRota model relies on three major criteria. Firstly, it depends on the appropriateness of the assumption that an observed crop mix is more or less stable over time as CropRota represents long term preferences of a farmer regarding agronomically justified crop choices. Secondly, the benefits of these choices are represented by the expert value judgments on crop sequences and crop frequency constraints. Thirdly, the level of performance as defined by the deviation of model output and observed land use data depends on the data quality as well as on the validation procedures.

Figure 12 shows the total area of important crops in the case study region from 2001 to 2007. Variations in crop shares can be observed on different levels and generally they will be larger on the farm level than on an aggregated regional level. This challenges the assumption of evenly distributed crop mixes and may be one of the reasons for the deviation between observed land use data and model results. Another reason on the farm level may be non-rational behavior or information imperfections of farmers. Nevertheless, choices on crop rotations beyond the recommendations of experts can still be rational for farmers, who take farm or even market specific circumstances into account. For example, high prices for certain crops may outweigh agronomic disadvantages of certain crop sequences and economically justify excessive use of agro-chemicals in order to handle increasing pressures from weeds and pests and nutrient depletions of soils.



[1] Temporary grass and red clover grass are one category in 2001.

Figure 12: Total area of important crops from 2001 to 2007 for all observed farms[1]

Expert judgments can be a source of inconsistencies as well (Dogliotti *et al.*, 2003; Mignolet *et al.*, 2004) but expert knowledge still dominates crop rotation design, particularly when quantitative data are missing (Poths, 1992). Even with proper judgments, the value point matrix in CropRota still reflects an aggregated view on the regional cropping conditions and may be inadequate for specific sites. The more heterogeneous a region is with respect to site conditions as well as farmers' attitudes and preferences, the more affected are crop rotation simulations.

Land use data inconsistencies can be another reason for a poor model fit. The IACS data base reports cropping decisions made in spring. It does neither take into account whether or not fields are harvested and how (e.g. silage corn vs. grain corn), nor is it based on a concise definition of crops in any case. For example, it depends more or less on farmers to judge, whether they are categorizing their temporary grass lands as 'red clover grass', 'temporary grass', or 'other grass'.

With respect to the validation procedure, two aspects of model performance are specifically important. Crop sequences are compared on the regional level for practical reasons, while the results have been generated on the farm level. These different scales may lead to interpretation biases of model results, if, for instance, the variances of farm level crop sequences are large and create compensating effects of positive and negative deviations. However, a case study application of CropRota on a farm level (Schönhart *et al.*, 2009) indicates similar model performances. Besides, our model validation procedure compares two- and three-crop sequences as a proxy for crop rotations, because observed data in a time series of seven years do not allow conclusions on particular crop rotations. Whether or not modeled crop rotations are realistic and whether or not farmers organize their cropping activities via crop rotations at all is a question left open. There are good reasons to believe that farmers are more flexible on annual crop choices than we assume in CropRota. They may not even stick to specific crop rotations (Mignolet *et al.*, 2004; Castellazzi *et al.*, 2007) but may instead react on production incentives, e.g. changes in output prices, on weather events, or substitute crop rotation effects by agro-chemicals (Robinson and Sutherland, 2002). However, crop rotations are a necessary input for many modeling approaches and environmental and production impact analyses. Therefore, they can be considered as theoretical proxies for crop sequences that may be applied practically today.

Linear programming models are frequently confronted with their difficulties to consider future innovations. CropRota generates crop rotations based on historic crop choices. The selection of already realistic crop rotations for specific farms or regions is a considerable advantage to models that only suggest a set of potentially feasible crop rotations. However, applications considering future innovative crop rotation practices are limited (Dogliotti *et al.*, 2003). CropRota can provide such alternative or new crop rotations for a farm or region by including alternative crop mixes.

Another common challenge to models is model size and computing power. CropRota is exponentially increasing with the number of crops and the length of crop rotations. Currently six-crop rotations are limited to observed crop mixes with less than 11 crops and five-crop rotations to mixes less than 18 crops. However, if longer crop sequences are not considered in the model, it may exclude certain crops from analysis (e.g. sugar beets). The number of crops is usually low at farm level, but this may not be true at regional or national level, which can increase the model size considerably. The demand of computing resources may even further increase, once intermediate crops or cropping systems with multiple crops per year are included. So far, CropRota has been applied only to cropping systems with one crop per year.

5. Conclusions

Crop rotations are an important property of agricultural systems and should be accounted for in integrated land use impact assessments. Published data on optimal crop rotations frequently reflect expert opinions, but there is little information on actual crop rotations beyond single farms. These crop rotations are important for bio-physical process models and economic land use optimization models, which are increasingly used to jointly assess economic and environmental impacts of alternative agricultural systems.

Empirical observations for larger regions may be prohibitive expensive and expert surveys can fail to deliver typical crop rotations (Mignolet *et al.*, 2004). Crop rotation models like CropRota seek to overcome these problems by generating sets of likely and optimal crop rotations based on crop statistics at farm and larger scales.

The case study application of CropRota on 579 farms proves its potential as a valuable tool for generating likely crop rotations, although there are still several options for further improvement. In case of input data specification, some challenges may be overcome by aggregating crop types into larger crop groups which are agronomically useful, e.g. ‘corn’ or ‘winter grain’ instead of its individual crops. Furthermore, expert judgments can be made less subjective by revealing their valuation criteria. For example, experts can be asked to value single effects of crop sequences, e.g. soil structure, diseases, pests, weeds, nitrogen, which for the final value point matrix are combined again (Leteinturier *et al.*, 2006). With respect to model validation, comparison of observed and modeled crop sequences can be complemented by judgments of farmers and experts on actually modeled crop rotations, e.g. through applying a delphi method. Model calibration may be further improved by replacing the manual adjustments of constraints and the value point matrix by model-internal mathematical algorithms. If not available, the observed data necessary for that may be generated from samples.

We are aware of the differences between modeled results and actual cropping plans. However, for the most important crop sequences covering a large amount of total crop lands, CropRota delivers reasonable results. If information on cropping plans is necessary, but reliable crop land use data is not available or crop rotations cannot be derived from such data sources, CropRota is a robust and straightforward tool to fill this data gap.

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Appendices

Appendix 1: Value point matrix for model approaches A and B

main crop

pre-crop	winter wheat	summer wheat	winter rye	mixed summer grain	winter barley	summer barley	oats	winter triticale	mixed winter grain	spelt wheat	other grain	grain corn	CCM	silage corn	green corn	peas	field beans	winter vetch	summer vetch	lupine	other legumes	saradella	red clover	red clover grass	alfalfa	temporary grass	other grass	rapeseed	mustard	flax	poppy seed	sweed	sugar beet	fodder beet	potatoes early	potatoes med	potatoes late	sun flower	soy bean	vegetables	pumpkin	fallow
winter wheat	4	4	6	6	6	6	8	6	6	4	5	10	10	10	10	10	10	10	10	10	10	10	6	6	6	6	8	10	8	10	10	10	10	10	10	10	10	10	10	10	10	6
summer wheat	4	4	8	4	8	6	8	6	5	4	5	10	10	10	10	10	10	10	8	10	10	8	6	6	4	4	6	8	8	10	8	8	10	10	10	10	10	10	10	10	8	8
winter rye	6	6	4	8	8	8	8	6	6	6	6	10	10	10	10	10	10	10	10	10	10	10	8	8	8	8	10	10	8	10	10	8	10	10	10	10	10	10	10	10	10	8
mixed summer grain	4	4	6	4	6	6	4	5	5	4	5	10	10	10	10	10	10	10	8	10	10	8	8	8	8	8	10	10	8	10	8	8	10	10	10	10	10	10	10	10	8	8
winter barley	4	6	6	5	4	6	8	6	5	4	5	10	10	10	10	10	10	10	10	10	10	10	8	8	8	8	10	10	8	10	10	10	10	10	10	10	10	10	10	10	10	8
summer barley	4	4	6	5	6	4	8	6	5	4	5	10	10	10	10	10	10	10	8	10	10	8	8	8	8	8	10	10	8	10	8	8	10	10	10	10	10	10	10	10	8	10
oats	8	4	8	7	8	6	2	8	8	8	7	10	10	10	10	10	10	10	8	10	10	8	8	8	8	8	10	8	8	10	8	8	10	10	10	10	10	10	10	10	8	10
winter triticale	4	6	6	5	6	8	8	4	5	4	5	10	10	10	10	10	10	10	8	10	10	8	8	8	8	8	10	8	8	10	8	8	10	10	10	10	10	10	10	10	8	6
mixed winter grain	6	4	6	4	6	6	8	5	6	6	5	10	10	10	10	10	10	10	10	10	10	8	8	8	8	8	10	10	8	10	8	8	10	10	10	10	10	10	10	10	8	6
spelt wheat	4	4	6	6	6	6	8	6	6	4	5	10	10	10	10	10	10	10	10	10	10	10	6	6	6	6	8	10	8	10	10	10	10	10	10	10	10	10	10	10	10	6
other grain	5	4	6	4	6	6	6	6	5	5	5	10	10	10	10	10	10	10	8	10	10	8	8	8	8	8	10	7	8	10	8	8	10	10	10	10	10	10	10	10	8	6
grain corn	8	8	0	8	0	8	8	0	4	8	5	8	8	8	8	8	8	0	10	10	10	8	8	8	8	8	6	0	8	8	8	8	6	6	6	6	6	8	10	6	8	6
CCM	8	10	0	10	0	10	8	0	6	8	6	8	8	8	8	10	10	0	10	10	10	8	8	8	8	8	10	0	8	6	8	8	4	4	8	10	10	10	10	4	8	6
silage corn	8	10	6	10	6	10	8	6	6	8	6	8	8	8	8	10	10	0	10	10	10	8	8	8	8	8	10	0	8	6	8	8	4	4	8	10	10	10	10	4	8	6
green corn	8	10	6	10	6	10	8	6	6	8	6	8	8	8	8	10	10	0	10	10	10	8	8	8	8	8	10	0	8	6	8	8	4	4	8	10	10	10	10	4	8	6
peas	10	6	10	6	10	6	4	10	10	10	6	10	10	10	10	2	2	2	4	2	4	4	2	2	2	4	6	6	6	4	4	6	6	6	10	10	10	4	4	4	4	4
field beans	10	6	8	8	6	6	8	10	10	10	6	10	10	10	10	2	2	2	2	2	2	4	2	2	2	4	6	6	2	2	2	6	10	10	10	10	10	2	2	4	4	4
winter vetch	10	6	8	6	8	6	6	8	8	10	6	8	8	8	8	2	2	2	2	4	2	4	0	0	0	0	2	6	0	4	0	6	6	6	8	6	6	6	6	4	4	2
summer vetch	10	6	8	6	8	6	6	8	8	10	6	8	8	8	8	2	2	2	2	2	2	2	0	0	0	0	2	6	0	4	0	6	6	6	8	6	6	6	6	4	4	2
lupine	10	6	6	6	8	6	6	10	10	10	10	10	10	10	10	2	2	4	4	2	4	2	0	0	0	2	6	6	0	6	0	6	10	10	10	10	10	6	2	4	4	2
other legumes	10	6	6	6	8	6	6	8	8	10	8	8	8	8	8	4	4	4	4	3	2	4	0	0	0	2	6	6	0	6	0	6	8	8	10	10	10	6	2	5	4	2
saradella	8	4	8	4	6	4	6	8	8	8	4	8	8	8	8	2	4	4	4	4	2	2	2	2	2	2	6	6	4	6	8	8	8	8	8	8	8	2	2	6	4	2
red clover	8	6	6	6	6	6	4	6	6	8	4	6	6	6	6	0	0	0	0	0	0	0	10	0	0	0	0	4	4	2	2	6	4	6	6	6	6	0	0	2	2	0
red clover grass	6	6	6	0	6	8	6	6	6	6	6	6	6	6	6	4	4	2	0	4	4	4	0	10	0	2	4	4	6	2	2	6	4	4	6	4	4	4	4	2	2	0
alfalfa	8	6	6	4	4	4	4	6	6	8	4	6	6	6	6	0	0	0	0	0	0	0	0	0	10	0	0	4	2	2	2	6	4	4	6	6	6	0	2	2	2	0
temporary grass	6	6	6	4	6	4	4	6	6	6	4	8	8	8	8	0	0	0	0	0	0	2	0	0	0	10	4	4	6	4	4	6	4	4	6	6	6	2	2	2	4	0
other grass	10	10	8	4	6	4	4	8	8	10	6	8	8	8	8	4	2	2	2	4	2	4	2	2	2	2	4	6	8	4	4	8	8	8	8	8	8	6	6	4	4	4
rapeseed	10	8	8	8	8	6	6	8	8	10	8	10	10	10	10	4	2	4	4	4	4	4	6	6	6	6	10	0	2	4	4	0	4	4	8	8	8	4	2	4	0	4
mustard	8	6	8	4	8	6	8	8	8	8	6	10	10	10	10	4	4	4	4	4	4	4	4	4	6	6	4	4	4	4	4	4	6	6	8	8	8	8	8	2	0	4
flax	8	8	8	8	8	10	10	10	8	8	8	10	10	10	10	4	4	4	4	4	4	4	2	2	2	4	6	2	4	0	0	6	8	8	8	8	8	8	8	8	0	4
poppy seed	8	6	8	6	8	6	6	8	8	8	6	6	6	6	6	4	4	4	4	4	4	4	2	2	2	2	4	6	4	4	4	6	6	6	6	6	6	4	4	4	4	4
sweed	8	8	2	8	6	2	8	4	4	8	6	8	8	8	8	6	6	6	6	6	6	6	4	4	4	4	6	2	2	4	4	2	4	4	6	6	6	4	4	2	2	4
sugar beet	8	10	0	10	0	10	10	4	4	8	8	8	8	8	8	6	6	4	4	4	6	4	4	2	4	4	8	0	8	4	6	0	2	2	8	8	8	6	6	4	4	4
fodder beet	8	10	4	10	6	10	10	4	4	8	8	8	8	8	8	6	6	4	4	4	6	4	4	2	4	4	8	0	8	4	6	0	2	2	8	8	8	6	6	4	4	4
potatoes early	10	6	8	10	8	6	10	10	10	10	10	8	8	8	8	8	8	10	8	4	4	6	4	4	4	4	6	10	4	4	4	0	10	10	2	2	2	10	10	4	4	4
potatoes med	10	6	8	10	8	6	10	10	10	10	10	8	8	8	8	8	8	4	8	4	4	6	4	4	4	4	6	10	4	4	4	0	10	10	2	2	2	10	10	4	4	4
potatoes late	10	6	8	10	8	6	10	8	8	10	8	8	8	8	8	6	6	4	4	4	4	6	4	4	4	4	6	10	4	4	4	0	10	10	2	2	2	10	10	4	4	4
sun flower	10	8	8	8	8	8	8	8	8	10	8	10	10	10	10	6	4	2	4	4	4	4	4	4	6	6	8	0	0	4	4	4	2	2	2	2	2	2	4	4	4	8
soy bean	10	8	6	8	8	10	10	8	10	10	8	6	6	6	6	2	2	2	2	2	2	2	2	2	2	2	4	2	2	4	4	4	8	8	8	8	8	4	4	4	4	4
vegetables	8	10	10	10	10	10	10	10	8	8	10	10	10	10	10	4	4	4	4	4	4	4	6	6	6	8	8	4	2	4	4	4	3	3	6	6	6	4	4	4	2	6
pumpkin	10	6	2	6	2	6	6	8	8	10	6	8	8	8	8	4	4	4	4	4	4	4	4	6	6	6	6	2	2	2	4	4	4	4	4	4	4	4	4	4	4	6
fallow	6	6	6	6	6	6	6	6	6	6	6	8	8	8	8	4	4	4	4	4	4	4	2	2	2	2	6	6	6	6	6	6	6	6	8	8	8	4	4	6	6	10

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