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The choice of crop rotations as an important model input – a case study from Saxony

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Abstract: Modelling systems are widely used for the assessment of agricultural management measures, e.g. to reduce nitrate loads as well as soil erosion or to avoid soil organic matter decline at different scales. However, modelling above the plot or farm scale resolution is challenged considerably by the limited availability and high uncertainty of bio-physical as well as management data, such as on crop rotations. Generally, information on applied crop rotations is scarce and highly aggregated in most cases (e.g. regional statistics). In this paper, we applied the crop rotation model CropRota [Schönhart et al. 2011] to derive crop rotations for 12 defined agricultural areas (240 – 3,200 km^2) in Saxony (Germany) based on regional statistics. We compared model results to observed land use data as well as expert-based crop rotations to proof the robustness and uncertainties related to CropRota as a tool to support integrated modelling studies.

We found that the use of 10 -15 crop rotations is sufficient to i) realize a quality in CropRota output data comparable to an expert knowledge system and ii) minimize the variations in output data because of different scenarios of intensity in crop cultivation. The number of crop rotations can be reduced with a better adaption of the used crop rotation table to regional circumstances and for regions with a lower heterogeneity in crop cultivation.

***Keywords**:* crop rotation; CropRota; integrated modelling; uncertainty

1 INTRODUCTION

Modelling systems are widely used for the assessment of agricultural management measures, e.g. to reduce nitrate loads as well as soil erosion or to avoid soil organic matter (SOM) decline just as unfavourable high SOM increase at different scales. However, modelling above the plot or farm scale resolution [e.g. for SOM reproduction see Franko et al. 2011] is challenged considerably by the limited availability and high uncertainty of bio-physical as well as management data, such as on crop rotations. Different studies, e.g. Hansen et al. [1999] and Thorsen et al. [2001], have been conducted to investigate the impact of aggregated cropping information on nitrate leaching using Monte Carlo techniques. The findings show a considerable effect of crop input data on simulated nitrogen losses. Therefore, data on crop rotations are required to fully employ the potential of bio-physical models for integrated assessments.

To overcome data constraints for small-scale case studies, crop rotations are often based on farm surveys, expert and modeller knowledge [e.g. Belcher et al. 2004;

van Ittersum et al. 2008; Rode et al. 2009], or model-based combinations of statistical data and expert knowledge [e.g. Bachinger and Zander 2006, Dogliotti et al. 2003]. To derive representative regional crop rotations, Lorenz et al. [2012], for example, tried to minimize the gap between observed crop rotations and generally used model input data by combining regional data from statistics, expert knowledge and field management data. For a review on methods to define crop rotations, see Castellazzi et al. [2008] and Schönhart et al. [2011]. Large scale model studies depend on more efficient methods to define crop rotation. Essential to such methods are their reliability to represent accurately applied crop rotations, their spatial and temporal compatibility of both, their required input data to available data sources as well as their output data to subsequently coupled models, and finally their applicability in research projects with time and financial constraints.

In this paper, we contribute to the research challenges on large scale crop rotation modelling by applying two distinct approaches to case study regions in Saxony, Germany. In approach 1, crop rotations have been generated with the crop rotation model CropRota [Schönhart et al. 2011] based on regional crop statistics. In approach 2, crop rotations have been determined by expert knowledge and field management data [Lorenz et al. 2012]. The objective of this publication is i) to demonstrate the workflow of CropRota by the example of agricultural regions in Saxony and ii) to compare the modelled crop rotations with crop rotations defined by expert knowledge. These findings provide an indication of the robustness and uncertainties related to CropRota as a tool to generate crop rotation input data for integrated modelling studies.

2 MATERIAL AND METHODS

2.1 Model description

CropRota is a generic linear programming model. It generates typical crop rotations and their relative shares based on crop mix input data from single farms up to regions. Thereby, we define crop rotations as recurrent crop series on a certain piece of land. Crop mixes represent the relative shares of crops grown on a farm or in a region over one to several years and are derived from observed farm data, regional land use statistics or expert knowledge. The generated typical crop rotations from CropRota maximize the total agronomic value (Z) on a farm or in a region. Z is the sum over the agronomic value (Y) of each single pre-crop – main crop sequence in all crop rotations. Y is derived from a crop rotation table (CRT) and is normalized by the relative share of a particular sequence. CRTs [e.g. Kolbe 2008, Vullioud 2005] frequently guide crop planting strategies of farmers and farming consultants. They include scores to value pre-crop – main crop sequences based on agronomic criteria such as risks on phyto-sanitary infection, weed infestation or nutrient availability. In the model, Y can be further adjusted by a correction factor to take into account agronomically less favorable crop rotations such as monocultures. CropRota is constrained to reproduce the observed crop mix. Thus, the total share of each crop summed over all typical crop rotations has to equal the observed crop mix, which implies that crop rotations only include crops represented in the crop mix input data. Optional constraints limit the frequency of self-intolerant crops or intolerant pairs of crops, such as sugar beets and rapeseeds. A full specification and case study application of CropRota is given in Schönhart et al. [2011].

2.2 Database

The study area of Saxony has about 18,400 km² and is located in the eastern part of Germany. It has an agricultural area of about 9,100 km^2, including about 7,200 km² of crop land [LfULG 2011a]. According to Winkler [1999] it can be divided into 12 sub-regions ranging in area from 240 – 3,200 km^2 based on basic natural conditions for agricultural production such as soil conditions, climate, water supply, altitude, and relief. Average observed crop mix data from 2005-2010 has been derived from the AFISS-system [agriculture and forestry information system of Saxony, LfULG 2011b], which includes a nearly full representation of arable land in Saxony.

CRTs are developed by agronomists. Deviations between CRTs result from a different weighing among agronomic factors (e.g. sowing and harvesting dates, nutrient availability and use, pest and disease transmission) or among agronomical, ecological, or economical objectives, as well as from regionally specific differences, e.g. soil and climate. Its generic setting enables CropRota to apply different CRTs as model input. Here, the CRTs presented in Schönhart et al. [2011] (CRT-S) and Kolbe [2008] (CRT-K) were used to clarify the sensitivity of the model results to model input parameters. CRT-S was developed and so far applied to the Austrian 'Mostviertel' region. CRT-K was developed under conditions of Saxony. To compare both, scores of the latter were transformed into the six categories of Schönhart et al. [2011], i.e. from zero (agronomically impossible sequences) to ten points (agronomically most desirable sequences).

To define two management scenarios (standard, intensive) different frequency constraint parameters (cf. table 1) were used. Due to the large number of different crops and the corresponding exponential increase in computing time, the length of modelled crop rotations has been limited to five years (approach 1).

Table 1. Frequency constraint parameters for the case study analysis

Crops	Standard	Intensive
corn, corn cob mix, silage corn, rye, winter wheat, grain (not specified)	max.1 in 2 yrs.	no constraint
summer barley, winter barley	max.1 in 2 yrs.	max.1 in 2 yrs.
triticale	max.1 in 3 yrs.	max.1 in 2 yrs.
potatoes, sugar beet, red clover grass, soy bean, field beans	max.1 in 4 yrs.	max.1 in 3 yrs.
oats, rape seed	max.1 in 4 yrs.	max.1 in 4 yrs.
alfalfa, red clover, sunflower	max.1 in 5 yrs.	max.1 in 4 yrs.
flax	max.1 in 5 yrs.	max.1 in 5 yrs.
peas, field beans	max.1 in 4 yrs.	max.1 in 3 yrs.

For approach 2 [see also Lorenz et al. 2012] a huge variety of field data was used to derive representative regional crop rotations for a region of about 4,800 km^2 around the city of Dresden. These field data and the derived representative crop rotations were checked against the full population survey of AFISS and the CropRota results for both CRTs and management scenarios (standard; intensive).

3 RESULTS AND DISCUSSION

At first, CRT-S and CRT-K were compared to reveal their differences (scores from CRT-S minus CRT-K). As figure 1 shows, the relative frequencies of the differences follow a Gaussian normal distribution curve. In most cases the two crop tables have a similar weighing of crop combinations. However, differences in the negative direction (18 % of pre-crop – main-crop combinations < -3) are caused by root-crops in combination with legumes/fodder as well as legumes/fodder combined with itself, whereas the positive differences (13 % > 3) are mainly caused by winter and summer wheat in combination with legumes/fodder and some combinations of different cereals. The highest differences are revealed for legumes and fodder crops such as temporary grassland. This is primarily caused by the different relevance of these crop sequences in the observed regions. With respect to temporary grassland, high livestock densities in the Austrian region lead to profitable grassland utilization over several years, which may be less the case for Saxony.

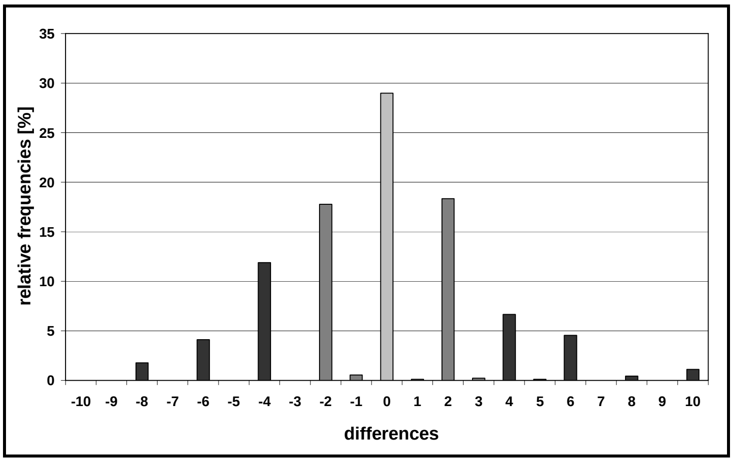

Figure 1. Relative frequencies in the differences of the scores from CRT-S and CRT-K

With respect to approach 1, CropRota modelled up to 24 possible crop rotations (cf. table 2) for the standard and for the intensive scenario with CRT-S. As it is marked in table 2, the number of crop rotations to achieve an intended relative share (resp. coverage of total area) differs between both management scenarios, because of the different frequency constraints (cf. table 1).

Table 2. Modeled crop rotations for the standard (above) and the intensive management scenario (below) for sub-region 3 with CRT-S

Nr.	intensity scenario	crop 1	crop 2	crop 3	crop 4	crop 5	cumulative relative shares
1	**standard**	silage corn	summer barley	winter rape	winter wheat	winter barley	**0,148**
2	**standard**	winter wheat	winter triticale	silage corn	summer barley	winter rape	**0,247**
3	**standard**	winter wheat	winter rape	winter wheat	winter barley	grain corn	**0,343**
4	**standard**	winter rape	winter wheat	winter barley	red clovergrass	winter wheat	**0,434**
5	**standard**	silage corn	summer barley				**0,509**
6	**standard**	temp. grass	temp. grass	temp. grass	winter barley	temp. grass	**0,583**
7	**standard**	winter rye	winter barley	winter rape	winter wheat	peas	**0,647**
8	**standard**	winter wheat	peas	winter wheat	winter barley	winter rape	**0,697**
9	**standard**	winter wheat	winter rape	winter wheat	sugarbeet	oats	**0,741**
10	**standard**	winter wheat	winter rape	winter wheat	winter barley	silage corn	**0,784**
11	**standard**	flax	oats	winter wheat	winter rape	winter wheat	**0,816**
12	**standard**	winter barley	alfalfa	winter wheat	winter rape	winter wheat	**0,844**
13	**standard**	silage corn	summer barley	winter rape	winter wheat	other grain	**0,865**
14	**standard**	winter wheat	winter rape	winter wheat	winter barley	potatoes early	**0,885**
15	**standard**	winter barley	potatoes med	winter wheat	winter rape	winter wheat	**0,905**
16	**standard**	winter rape	winter wheat	winter barley	potatoes late	winter wheat	**0,924**
17	**standard**	winter wheat	winter barley	winter rape	winter wheat	oats	**0,944**
18	**standard**	winter wheat	winter rape	winter wheat	winter barley	red clover	**0,961**
19	**standard**	winter rye	silage corn	winter wheat	winter rape	winter wheat	**0,974**
20	**standard**	winter wheat	winter barley	winter rape	winter wheat	CCM	**0,983**
21	**standard**	summer barley	winter rape	winter wheat	oats	silage corn	**0,989**
22	**standard**	winter rape	winter wheat	winter barley	sunflower	winter wheat	**0,995**
23	**standard**	winter rape	winter wheat	field beans	winter wheat	winter barley	**1,000**
1	**intensive**	summer barley	silage corn				**0,175**
2	**intensive**	winter barley	grain corn	winter wheat	winter rape	winter wheat	**0,271**
3	**intensive**	winter wheat	winter barley	red clovergrass	winter wheat	winter rape	**0,361**
4	**intensive**	winter rape	winter wheat	oats	winter barley		**0,442**
5	**intensive**	winter wheat	winter rape	winter wheat	peas		**0,523**
6	**intensive**	winter barley	temp. grass	temp. grass	temp. grass	temp. grass	**0,597**
7	**intensive**	winter barley	winter triticale	winter barley	winter rape	winter wheat	**0,664**
8	**intensive**	winter rye	winter barley	winter rape	winter wheat		**0,726**
9	**intensive**	silage corn	winter wheat	winter rape	winter wheat		**0,772**
10	**intensive**	sugarbeet	winter wheat	winter rape	winter wheat		**0,807**
11	**intensive**	winter barley	winter rape	winter wheat	flax	winter triticale	**0,839**
12	**intensive**	alfalfa	winter wheat	winter rape	winter wheat	winter barley	**0,867**
13	**intensive**	other grain	winter barley	winter rape	winter wheat	winter barley	**0,888**
14	**intensive**	silage corn	summer barley	winter rape	winter wheat		**0,909**
15	**intensive**	red clover	winter wheat	winter rape	winter wheat	winter barley	**0,927**
16	**intensive**	winter wheat	potatoes med	winter wheat	winter rape		**0,942**
17	**intensive**	potatoes early	winter wheat	winter rape	winter wheat		**0,958**
18	**intensive**	potatoes late	winter wheat	winter rape	winter wheat		**0,974**
19	**intensive**	winter wheat	peas	winter barley	winter rape		**0,983**
20	**intensive**	winter rape	winter wheat	CCM	winter wheat		**0,990**
21	**intensive**	winter wheat	sunflower	winter wheat	winter rape		**0,995**
22	**intensive**	winter wheat	field beans	winter wheat	winter rape		**0,999**
23	**intensive**	peas	winter barley	winter rape	winter wheat	winter barley	**1,000**

The share of each crop in these modelled crop rotations was checked against the full population survey (2005-2010, AFISS) in the 12 regions of Saxony (cf. table 3). Only small differences between the given full population survey and the crop rotations from CropRota were found at the level of single crops. If all 24 modelled crop rotations were aggregated, we could not find differences even between the regions. The root mean square error [RMSE, e.g. Loague and Green 1991] were calculated for all crops and 12 regions. For the CRT-S and CRT-K we found similar RMSE of 0.00001 for the intensive and standard scenario. The RMSE increase with decreasing thresholds of regional representativeness compared to the given AFISS statistics (cf. table 3).

Table 3. RMSE for the 12 regions and all crops

RMSE	CRT-S		CRT-K	
cumulative relative share	normal	intensive	normal	intensive
100	0,00001	0,00001	0,00001	0,00001
95	0,00308	0,00299	0,00288	0,00300
90	0,00578	0,00586	0,00554	0,00593
85	0,00832	0,00889	0,00832	0,00825
80	0,01101	0,01162	0,01154	0,01126
75	0,01371	0,01466	0,01426	0,01394
70	0,01577	0,01667	0,01717	0,01712

To specify the importance of individual crop rotations in a region, CropRota calculates its relative share on total arable land. The resulting cumulative shares were used to verify the minimum number (mn) of crop rotations needed for a defined threshold of regional representativeness (cf. table 4), i.e. a cumulative relative share of 0.9 means that the corresponding number of crop rotations represent a total area of 90 %.

Table 4. Mean minimum number of crop rotations (mn) needed for a defined threshold of regional representativeness for the 12 regions of Saxony

cumulative relative share	mn (CRT-S)	mn (CRT-K)
> 0.75	10	8
> 0.80	11	9
> 0.90	15	13

The cumulative relative shares and their corresponding number of crop rotations are different among sub-regions and both management scenarios (standard, intensive; see figure 2). Sub-regions 3 and 8 are those with the highest heterogeneity in crop cultivation and require more crop rotations for an assumed cumulative share. In some other regions the number of crop rotations to achieve a particular cumulative share is lower. CRT-K leads to slightly lower minimum numbers of crop rotations then CRT-S, because it is adapted to regional circumstances.

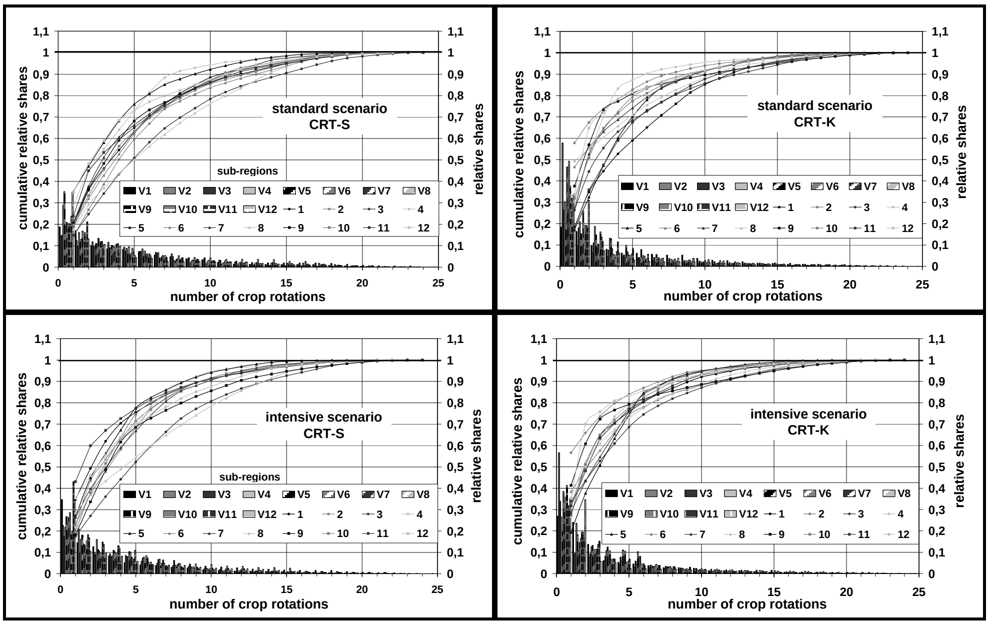

Figure 2. Cumulative relative shares depending on crop rotation number and sub-region (above: standard management scenario; below: intensive management scenario; left: CRT-S; right: CRT-K)

Additionally to the CRT, crop rotations are affected by the frequency constraints (see table 1). To verify their impacts, two management scenarios were analyzed. The maximum differences of the cumulative relative shares in both scenarios and both CRTs ranges from -0.2 to 0.2 (cf. figure 3). To fall below a defined threshold of difference in the cumulative relative shares of both management scenarios a minimum number of crop rotations (mn) according to table 5 is needed. As figure 3 reveals, differences between the management scenarios (standard, intensive) became larger with a decreasing number of considered crop rotations, i.e. lower cumulative relative shares. Consequently, a compromise has to be found according to the modelling task for each specific sub-region.

Table 5. Mean minimum number of crop rotations (mn) needed for a defined difference in cumulative relative shares for the 12 regions of Saxony between standard and intensive management scenario

Difference in cumulative relative shares	mn (CRT-S)	mn (CRT-K)
< 0,10	7	9
< 0,05	15	12
< 0,01	19	18

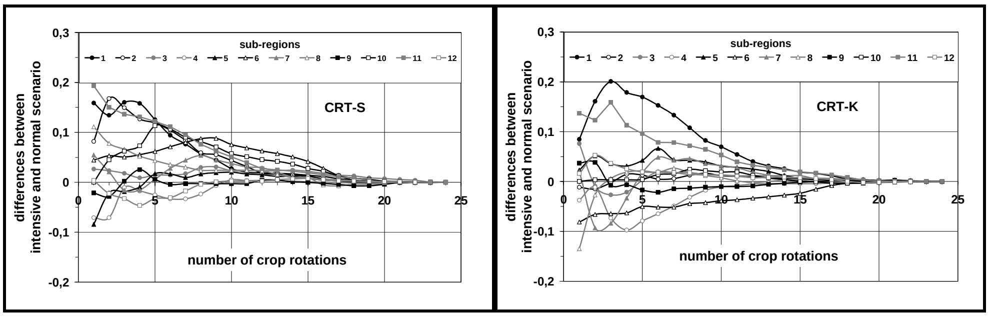

Figure 3. Differences in the model output between the intensive and standard management scenario

Derived representative regional crop rotations from approach 2 were checked against observed AFISS data and the CropRota output (approach 1) at the level of single crops, i.e. their cumulative relative share. The model output of CropRota (approach 1) is displayed for the two CRTs and both scenarios in figure 4. Sub-region 3 was used for comparison, because it is completely represented in both approaches and the AFISS data base.

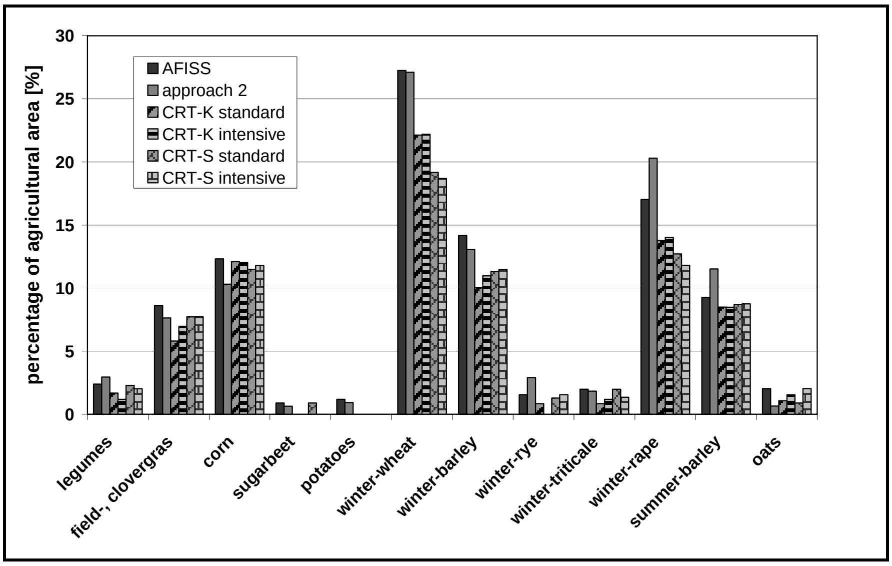

Figure 4. Comparison of CropRota output (approach 1) to expert knowledge and statistics (approach 2) for sub-region 3 at the level of single crops

To compare both approaches crop rotations generated by CropRota (approach 1) were considered up to a cumulative relative share of > 0.8 (i.e. 80 % of the agricultural area), because it corresponds best with the definition of 10 crop rotations for every observed sub-region in approach 2. This procedure should preserve the comparability of both approaches. The differences between the crop rotations of approach 1 and 2 are the largest for the cumulative relative shares of winter wheat and winter-rape. These are the crops with the highest spatial representativeness in the observed study area. Therefore, they are part of all 23 modelled crop rotations and are mainly affected by a limitation of crop rotations up to a certain cumulative relative share. In approach 2 winter-rape and summer-barley are slightly overrepresented. This is impossible for CropRota because the full model results represent the given statistical input data and a reduction of the considered crop rotations will likely lead to an underestimation (cf. table 3). In general, both approaches lead to a sound representation of the given regional statistical data.

4 CONCLUSIONS

Crop rotations are frequently required model inputs to agricultural and ecological system models. This study compares two different approaches for constructing crop rotations, i.e. the crop rotation model CropRota (approach 1) and expert-based representative crop rotations (approach 2).

A comparison between two model runs with parameters from an Austrian case study application (CRT-S) and parameters adapted to Saxony (CRT-K) reveals the importance of model specification according to regional contexts. Due to its generic character, adaption of the model parameters, i.e. the CRT as well as the frequency constraints, are straightforward in CropRota. Consequently, advantages of approach 1 include low research resource demand as an increasingly important prerequisite to integrated model studies. Model input data such as crop mixes have been derived from readily available observed land use data. With respect to the model output, CropRota ranks crop rotations by a relative share, which allows judgements on the importance of single crop rotations as well as on the quality of the model output.

To achieve a quality in output data comparable to the expert knowledge system (approach 2), a cumulative relative share of modelled crop rotations of 0.9 should be achieved, i.e. selected crop rotations should cover a total area of 90 %. This leads to a minimum number of 10-15 crop rotations for the observed regions (depending on sub-region conditions) used for further model applications, to ensure an appropriate regional representativeness of crop cultivation. By comparing the model output to the expert knowledge system (approach 2), we get some hints for the practicability and reliability of CropRota and conclude, that it offers a wide range of possible applications in the field of land use and land-cover change modeling (SOM-turnover, erosion, N-leaching etc.).

Nevertheless, one has to acknowledge the uncertainties related to expert-based crop rotation definition and modelling procedures. With respect to CropRota, a crucial point to model uncertainty are the inherent assumptions that (a) farmer’s crop choices are based on agronomic criteria, which are finally represented in observed crop mixes and that (b) relevant agronomic criteria are taken into account by the crop rotation table and some model constraints. With respect to regional modeling, it is assumed that (c) a crop mix aggregated over several farms results in crop rotations at least similar to those at the individual farm level. These rather strong assumptions are challenged by decisions based on other than agronomic criteria or substitution of crop rotation effects by farm inputs. With respect to (c), aggregation biases may occur for applications at larger regional levels. However, this latter point may also be one of CropRota’s strength, i.e. the reduction of numerous possible crop rotations to a selected number of most likely applied typical crop rotations. With respect to parameter uncertainty, such as the expert-based crop rotation table or the frequency constraints, experts may weigh isolated agronomic effects differently from farmers and may not take into account heterogeneous bio-physical conditions in a region such as soil characteristics, altitude or slope. To reveal and consequently tackle uncertainty in crop rotation models, more research is required on the role and composition of crop rotations on different scales.

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