Institute for Food and Resource Economics

University of Bonn

Discussion Paper 2020:6

‘Fruchtfolge’: A crop rotation decision support system for optimizing cropping choices with big data and spatially explicit modeling

Christoph Pahmeyer, Till Kuhn, Wolfgang Britz

The series " Food and Resource Economics, Discussion Paper" contains preliminary manuscripts which are not (yet) published in professional journals, but have been subjected to an internal review. Comments and criticisms are welcome and should be sent to the author(s) directly. All citations need to be cleared with the corresponding author or the editor.

Editor: Thomas Heckelei

Institute for Food and Resource Economics

University of Bonn

Nußallee 21

53115 Bonn, Germany

Phone: +49-228-732332

Fax: +49-228-734693

E-mail: thomas.heckelei@ilr.uni-bonn.de

‘Fruchtfolge’: A crop rotation decision support system for optimizing cropping choices with big data and spatially explicit modeling

Christoph Pahmeyer, Till Kuhn, Wolfgang Britz

Abstract

Deciding on which crop to plant on a field and how to fertilize it has become increasingly complex as volatile markets, location factors as well as policy restrictions need to be considered simultaneously. To assist farmers in this process, we develop the web-based, open source decision support system ‘Fruchtfolge’ (German for ‘crop rotation’). It provides decision makers with a crop and management recommendation for each field based on the solution of a single farm optimization model. The optimization model accounts for field specific location factors, labor endowments, field-to-farm distances and policy restrictions such as measures linked to the EU Nitrates Directives and the Greening of the EU Common Agricultural Policy. ‘Fruchtfolge’ is user-friendly by automatically including big data related to farm, location and management characteristics and providing instant feedback on alternative management choices. This way, creating a first optimal cropping plan generally requires less than five minutes. We apply the decision support system to a German case study farm which manages fields outside and inside a nitrate sensitive area. In the year 2021, revised fertilization regulations come in force in Germany, which amongst others lowers maximal allowed nitrogen applications relative to crop nutrient needs in nitrate sensitive areas. The regulations provoke profit losses of up to 15% for the former optimal crop rotation. The optimal adaptation strategy proposed by ‘Fruchfolge’ diminishes this loss to 10%. The reduction in profit loss clearly underlines the benefits of our support tool to take optimal cropping decisions in a complex environment. Future research should identify barriers of farmers to apply decision support systems and upon availability, integrate more detailed crop and field specific sensor data.

Keywords: big data, Decision Support System, Nitrates Directive, Fertilization Ordinance, farm level simulation model

JEL classification: C63, Q16, Q52, M15

1 Introduction

Every year, farmers need to decide anew which crops to plant on each of their fields. Their choices need to reflect a growing number of determinants. On the individual field level, location factors such as soil types and crop rotational effects, as well as technological, structural, and economical factors need to be considered (Kuhlmann, 2015). At farm scale, the cropping plan needs to fit to the farmer's labor and machinery endowments. Furthermore, command-and-control measures related to agri-environmental legislation need to be considered. The German implementation of the EU Nitrates Directive as the core regulation to protect water bodies from nitrate emissions from agriculture provides a striking example. It prescribes complex field specific management standards, for instance depending on the chosen crop, its yields, and the nitrogen content of the soil.

In the past, multiple attempts at assisting decision makers with the ‘cropping choice problem’ have been made. Methodologically, mathematical programming (including linear programming) has proven to be a powerful tool for the analysis of resource allocation choices (Hazell and Norton, 1986). McCarl et al. (1977) used linear programming to create an income maximizing cropping pattern for commercial grain farms in the Midwest. Their approach required farmers to fill an input form with their data, subsequently being evaluated by researchers. However, without research extension interaction, farm planning use of the model was found to be not generally practical.

Subsequent approaches focused on extensions to linear programming models as the inclusion of risk modeling (Mußhoff and Hirschauer, 2006a, 2004), or applications in the context of policy analysis (Galán-Martín et al., 2015; Louhichi et al., 2010). However, all the models solely returned optimal crop shares at farm scale. Compared to optimizing the spatially explicit crop allocation, this significantly reduces data needs and model complexity but disregards the heterogeneity of the individual fields and their spatial characteristics. It eventually leads to a sub-optimal solution to the original planning problem and, when used as DSS, leaves the decision taker with the daunting task to allocate the proposed optimal shares at farm scale to individual fields. Only Radulescu and Radulescu (2012) describe a DSS based on a portfolio selection model for crop planning under risk, that provides the user with a crop recommendation on a per field basis. However, their approach requires manual input for all crop and field related data and does not incorporate policy restrictions and manure allocation.

Despite these efforts, models to support cropping choices based on mathematical programming have rarely been adopted by farmers and farm advisers (Mußhoff and Hirschauer, 2016). As one of the main reasons for the relatively low uptake of such models, referred to as decision support systems (DSS) when focused on supporting farmers’ management choices, Mußhoff and Hirschauer (2016) identify the high data requirements of mathematical programming.

In the underlying manuscript, we present the web-based DSS ‘Fruchtfolge’ (German for crop rotation) which supports farmers' in making optimal crop and crop management choices in a complex environment[1]. Fruchtfolge provides its users with a crop recommendation and manure application strategy for each of their fields, automatically incorporating big data from multiple sources related to farm, location, and management characteristics. By combining these datasets, a highly detailed single farm model is created and solved in real-time in the background, without requiring extensive user input. The model automatically adheres to legal restrictions from the German Fertilization Ordinance (FO), implementing the Nitrates Directive, and the Greening obligations of the EU Common Agricultural Policy. Following best practices of 'user-centered design' (Parker and Sinclair, 2001; Rose et al., 2017, 2016), the maximum required time to create an initial optimal cropping plan is targeted at 5 minutes, including application signup and data entry.

The contribution of the paper is twofold. First, we present Fruchtfolge as an innovative and unique DSS targeting (German) farmers and farm advisors. Second, we apply it to an exemplary farm which faces tighter measures of the FO, mainly coming in force from 2021 onwards, in order to illustrates the benefits of Fruchtfolge to find optimal cropping plans in complex environments.

2 Decision support system Fruchtfolge

2.1 *System overview*

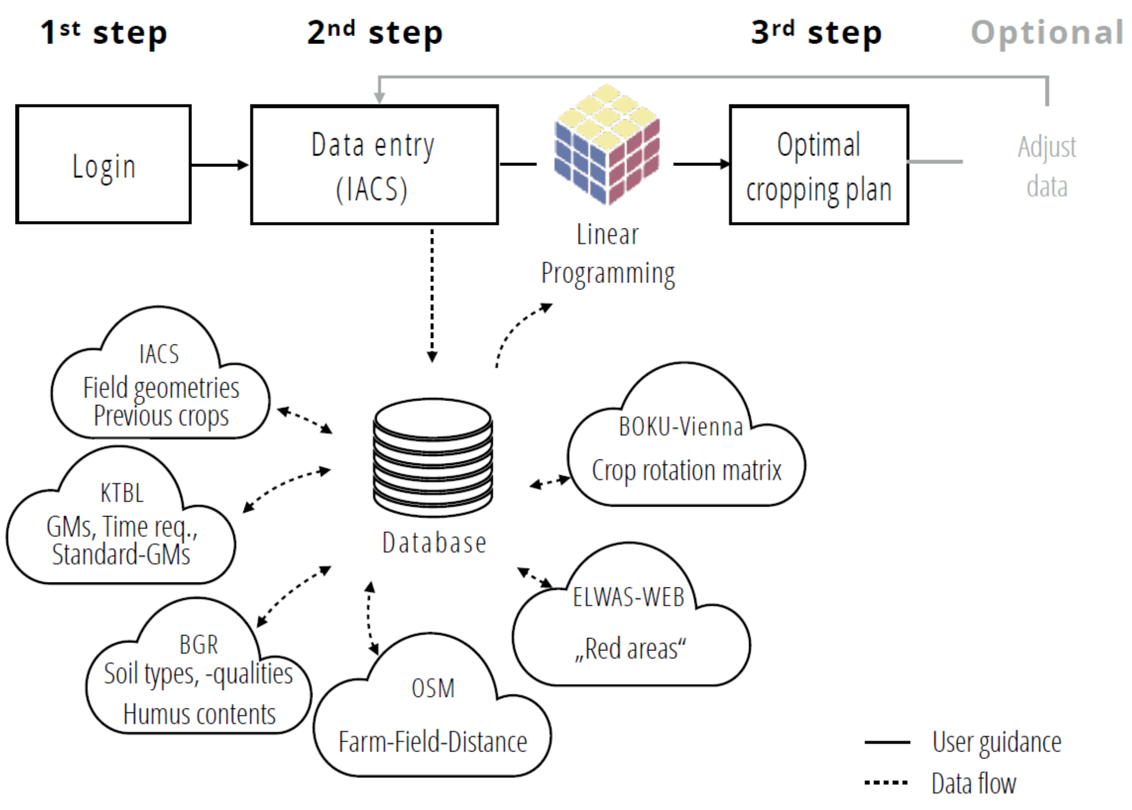
"Fruchtfolge" is built in an effort to create a user-centered, simple to use DSS to provide profit maximal field specific cropping choices and fertilization strategies. Its development is based on best practices in agricultural DSS design outlined by Rose (2016), and experiences from established DSS such as ValorE (Acutis et al., 2014) or vite.net® (Rossi et al., 2014). Emphasis is put on the DSS core factors 'performance' and 'ease-of-use'.

Figure 1 displays a systematic overview of Fruchtfolge. Three main steps are required in order to receive a first optimization result by the DSS. First, the user needs to initially sign-up on the website choosing a password, providing an E-Mail address as its user-id and the address of the farm premises. The address is required for the calculation of farm-to-field distances at a later stage. Like other web services, upon completion of the initial signup, users can later login again to the DSS using their E-Mail address and password and find all so far entered input and results. In a second step, users are asked to enter their so-called customer reference number (CRN, ZID number in Germany) which is available for every farm having applied for direct payments under the EU Common Agricultural Policy.

[1] The Fruchtfolge DSS is hosted at the following URL: https://fruchtfolge.agp.uni-bonn.de/
Please see the supplementary video for a short overview of the Fruchtfolge DSS [English], as well as the user documentation hosted at https://fruchtfolge.agp.uni-bonn.de/documentation/ [German]

Subsequently, the necessary data to optimize a cropping plan is downloaded automatically in the background and combined to a first version of the mixed integer linear programming (MILP) model without further action required from the user. Once this initial model is solved, the user is presented with the optimal cropping plan in a table and a map view with supporting graphs. In addition, a so-called fertilizing planning sheets as required by the German Fertilization Ordinance (FO) are generated. Next, the user can adjust input parameters such as prices, costs, yields, or crop share constraints and re-run the model. In the following, the technical procedure of the data acquisition is further explained.

Figure 1: System architecture of Fruchtfolge



Further descriptions of the data sources can be found in Table 1.

2.2 *Graphical User Interface and technical implementation*

The Graphical User Interface (GUI) of the Fruchtfolge DSS enables the communication between the user, the data base and the underlying bio-economic model. The GUI shields off details of the technical implementation from the user, allowing them to successfully use the DSS without requiring in-depth knowledge about the underlying model (Britz, 2014). As illustrated in the top part of Figure 1, the GUI is divided into three main parts: 1) The landing or login page, 2) data input pages (divided into sub-pages for fields, crops and constraints), and 3) the results page. Technically, the Fruchtfolge DSS is built as a progressive web application written in Node.js (server side) and JavaScript (client side). Opposed to traditional desktop applications which users have to download and install on their PC, progressive web applications are loaded on the fly and have the benefit of being portable across a whole range of devices (computers, tablets, smartphones) and operating systems without requiring substantial changes to their codebase. Users also automatically use the most up-to-date version of the DSS when visiting the website. A progressive web application requires constant internet access to deliver all of its features. According to a survey by the digital association Bitkom (2020), 82% of the German farmers already use digital technologies on their farm. Therefore, internet access and familiarity with digital technologies cannot be considered as a serious restriction regarding the use of a progressive web application. Fruchtfolge is open source and open access. Development of the application and its different sub-modules is steered from a public code versioning repository[2].

2.3 *Farm data import and big data use*

Detailed planning data is required for the optimization of a field specific farm cropping plan. In order to minimize manual data input, an importing routine in Fruchtfolge gathers automatically default information as detailed as possible for each field, crop and the farm as a whole. Users are free to overwrite each piece of information.

The different data sources automatically imported are displayed in Table 1 and in the bottom part of Figure 1. The CRN (ZID) provided by the user to gives access to the North Rhine-Westphalian IACS (Integrated Administration and Control System) database to collect data on the crops grown in previous years on each of the farm's fields along

The KTBL database reports on time and machinery requirements, as well as variable and fixed costs depending on soil types, farm-to-field distances, yield levels and field sizes for individual field operations. The data is available for almost 100 crops, resulting in over 6,000,000 available data points. The time requirements for the single field operations allow estimating the required work time for a cropping plan in each month. Furthermore, the database also provides an estimate for the monthly available field working days depending on the field operation and region which can be interactively updated on demand. If the farmer enters available work hours per month, these data allow introducing monthly labor use constraints in the model. Basic parameters relating to cropping choice such as

[2] The main code versioning repository, as well as technical documentations of the different modules used in 'Fruchtfolge' can be found under: https://github.com/fruchtfolge

minimum rotational break years, previous crop effects (crop rotation matrix), and minimum soil requirements are taken from the CropRota model (Schönhart et al., 2011).

Table 1: Source and description of external data used in the Fruchtfolge DSS

Name	*Description*	*URL of the data*	*Application programming interface (API) to Fruchtfolge*
IACS database	The IACS (Integrated Administration and Control System) database includes field geometries as well as previous crops cultivated on the field for each farm in North Rhine-Westphalia.	https://www.lwk-verfahren.de/DownloadPortal/pages/index.action	https://github.com/fruchtfolge/elan-api
KTBL database	The KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft) provides open data access to farm planning data such as regionalized historical yields, prices, and direct costs as well as field working operations depending on farm-field distances, soil types and field sizes.	https://srv.ktbl.de/doc/dev.en.html	https://github.com/fruchtfolge/KTBL-APIs
BGR maps	The BGR (Bundesamt für Geowissenschaften und Rohstoffe) provides maps regarding soil types, quality as well as humus contents.	https://www.bgr.bund.de/EN/Themen/Boden/boden_node_en.html	https://github.com/fruchtfolge/BGR-APIs
OSM	OSM (Open Street Maps) data is used to compute the field to farm distance for each field, relying on OSRM (Open Source Routing Machine).	https://github.com/Project-OSRM/osrm-backend	-

ELWAS-WEB	Outlines of 'red' areas according to the specification of Fertilization Ordinance at federal state level	https://www.elwasweb.nrw.de/elwas-web/index.jsf#	-
CropRota model, BOKU	The CropRota model (Schönhart et al., 2011) developed at the BOKU Vienna provides a value point matrix for different previous and subsequent crop combinations.	https://wpr.boku.ac.at/wpr_dp/DP-45-2009.pdf	-

Nutrient contents, loss factors for the manure(s) and manure output per pig housing place are chosen according to the FO (BMEL, 2017). Along with the number of animal places provided by the user, this allows calculating the quantity of manure (liquid and solid) at farm level. The model depicts different nitrogen fertilizing levels and related yields for each crop based on N-response curves from Heyn & Olfs (2018). This is especially relevant under the FO 2020 where farmers have to reduce nitrogen fertilizer below the crop needs as in 'red' areas. Fruchtfolge either considers the restrictions of the FO 2017 or the FO 2020, depending on the farmer's choice. Primarily, both FO restrict the amount of manure and mineral fertilizer applied, as well as the legal time window of the application. As the regulations are part of the case study analysis, they are described in section 3.1.

The combination of the different data sources allows calculating gross margins and monthly labor requirements for each individual field and crop. For each field, the calculation reflects farm-to-field distance and size along with yield differences based on its soil quality and previous crop effects. The values are further differentiated for the following management options: varying levels of liquid and solid manure, cultivation of a catch crop (Boolean), manure application in autumn (Boolean), and different levels of nitrogen fertilizer reduction. Manure spreading options range from 0 m³ ha^{-1} to 60 m³ ha^{-1} in 5 m³ steps reflecting typical manure barrel sizes.

Data on agronomic as well as on legislative constraints complements the information on farming operations and location characteristics. The field and crop specific minimum rotational breaks are complemented by maximum crop shares at farm level to avoid an overspecialization on the most profitable crops in the current year - the only one subject to optimization. To give an example, a minimum rotation break of two years for a crop on a field results in a maximum share of 33% ($1/(rotation\ break + 1)$) of the crop on the farms total cultivation area. Furthermore, the rules from the Greening obligation of the Common Agricultural Policy regarding minimum crop diversity and ecological focus area are considered in the DSS.

2.4 *Decision problem and optimization*

The calculations detailed above populate a matrix of all possible management options for each crop and field. All calculations are performed automatically in the background when new data are entered. An example of such a matrix is shown in Table 2. Each column of the matrix represents the (theoretically) possible cultivation options for one crop and field combination, characterized by the amount of manure to be spread, whether manure is applied in autumn, and whether a catch crop is cultivated before the main crop. If the FO 2020 proposal is active, an additional column indicates whether nitrogen fertilization should be reduced (and if yes, to which extent) for all fields that lie within a 'red' area as designated by the FO 2020.

This matrix depicts the decision space of the farmer. Without the support of the DSS, the decision maker would need to pick exactly one of these many options for each field, considering agronomic, economic, market, and legal constraints, partly at field, partly at farm level. Using a mathematical programming model, Fruchtfolge finds the optimal solution from the matrix which simultaneously considers all of these constraints. Based on its solution, Fruchtfolge proposes to the user (1) which crop to plant and (2) how much manure and mineral fertilizer to apply on each field.

Table 2: Example of a cropping matrix showing all possible cropping options for each field, crop, and manure combination.

Field	*Crop*	*Manure [m^3/ha]*	*Autumn fertilization*	*Catch crop*
Field 1	Winter wheat	0	no	no
Field 1	Winter wheat	5	no	no
Field 1	Winter wheat	5	yes	no
...				
Field 20	Silage maize	60	yes	yes

As an example, a farm endowed with 20 fields and considering 5 different crops results in matrix with 5,200 columns, given 13 fixed manure spreading amounts, and the options of using or not manure application in autumn and a catch crop: $20 \cdot 5 \cdot 13 \cdot 2 \cdot 2 = 5.200$. If these 20 fields were located in a 'red' area, the matrix would even comprise 26,000 columns considering five possible N-reduction levels for each former option. Each column could either be chosen or not (Boolean), as we do not consider mixing crops or options on a field. This results in $2^{5,200}$ or even $2^{26,000}$ potential farm plans.

To address this complex decision problem for the user, a mixed integer linear programming model (MILP) is created and solved on the server side of the application. This offers a controlled technical environment with access to higher computing power, ensures that time for model generation and solve are independent from the user's hardware, and avoids installing the software for model generation and solution on the farmer's computer. As a first step, the matrix containing individual gross margins for each field, crop, manure amount, catch crop, and autumn fertilization option is created. Besides the gross margin, each column comprises entries which relate to farm-wide constraints: monthly labor needs, ecological focus area factors, as well as fertilizer demand. The resulting matrix enters a model which maximizes the farm's gross margin as the sum of the individual gross margins by field, crop, manure, catch crop, and autumn fertilization option multiplied with the (binary) decision variable indicating whether this option is active on the field or not. The model is written in the GAMS programming language (GAMS Development Corporation, 2019), and solved using the CPLEX MILP solver (IBM ILOG CPLEX, 2009). The source code of the model can be found in the supplementary material file[3].

For simplicity but without loss of generality, we summarized the manure amount, autumn fertilization, and catch crop options under the label *k*.

Following the notation used by Hazell and Norton (1986), the model can be written as follows:

$$\max_{v_{j,k,l}} tcm = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} cm_{j,k,l} \cdot ha_l \cdot v_{j,k,l}$$

subject to

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} a_{r,j,k,l} \cdot ha_l \cdot v_{j,k,l} \leq b_r, \forall\, r = 1,2,\ldots,R$$

where

tcm	Total expected contribution margin of the farm

[3] The source code of the model is available in the following versioning repository: https://github.com/fruchtfolge/model. The model version used in the manuscript can be found under the following DOI reference: 10.5281/zenodo.3626740.

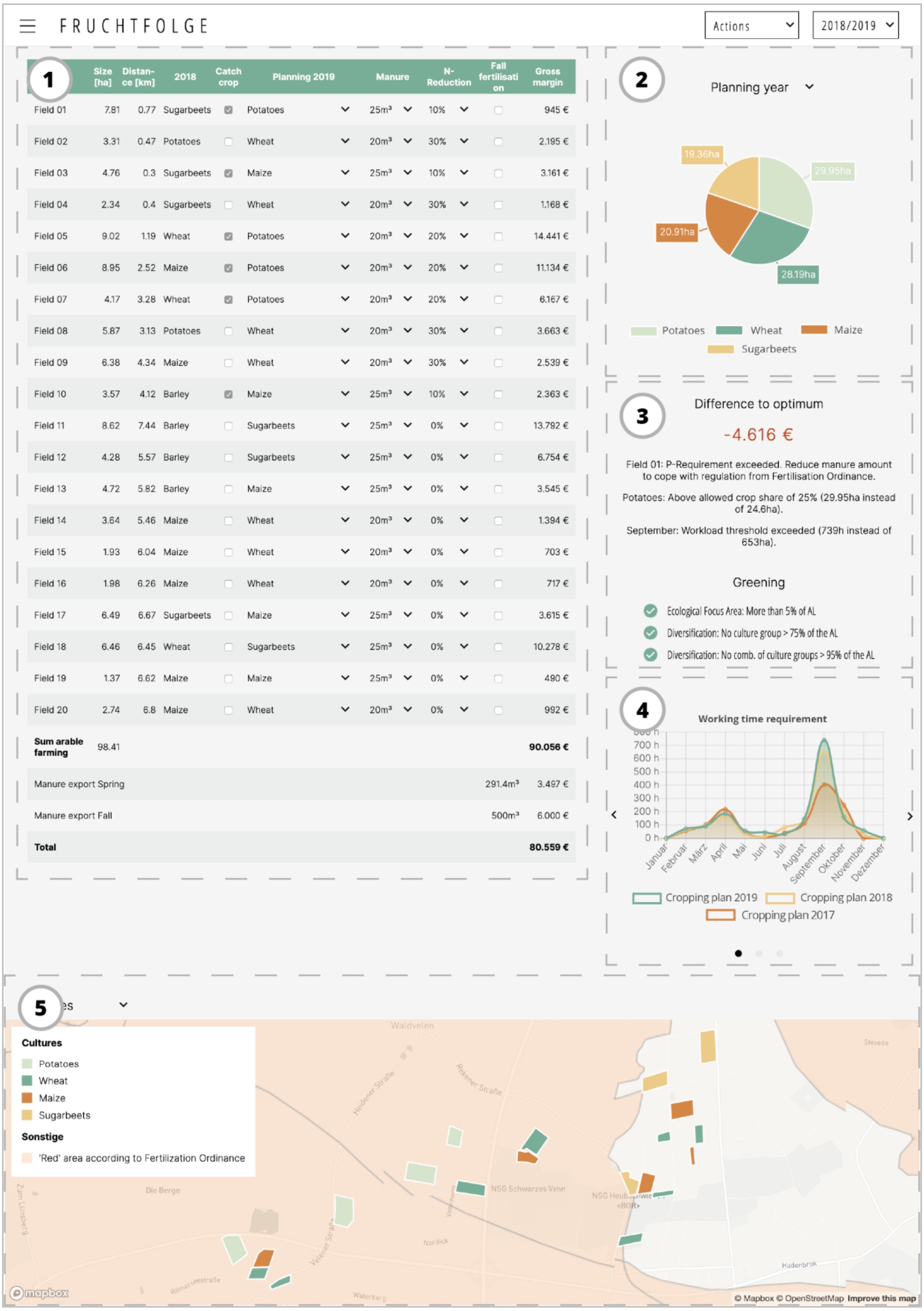
$cm_{j,k,l}$	Expected contribution margin per ha for crop *j* combined with management option *k* on field *l*
ha_l	Size of field *l* in ha
$v_{j,k,l}$	Binary variable stating if crop *j* combined with management option *k* is present on field *l*
$a_{r,j,k,l}$	Coefficient of crop *j* combined with management option *k* on field *l* relating to resource or legal constraint r
b_r	Level of resource or legal constraint r

2.5 *Output*

Solving the model generally requires only a couple of seconds. Once the model is solved on the server, results are retrieved, processed and presented to the farmer in a sub page of the web application. An exemplary results page is displayed in Figure 2. The results page offers (1) a table showing the crop recommendation for each field, (2) a box indicating compliance with the greening legislation, (3) a pie chart with crop shares at farm level and information on the deviation from the optimal program when farmers adjust the cropping choice and management option (section 2.6), (4) two line charts, one displaying for the current year the monthly required work load and manure storage levels and a second one depicting profits over the last ten years under current year’s plan at observed historic yields and prices, and finally (5) a map showing the spatial allocation of the different crops and the manure allocation. Furthermore, Fruchtfolge provides farmers with a field specific nitrogen and phosphate fertilizing planning sheet as required by the FO.

The results page offers (1) a table showing the crop recommendation for each field, (2) a pie chart with crop shares at farm level, (3) a box indicating deviations against constraints and the influence of the violation on the farm profit, as well as compliance with the greening legislation when farmers adjust the recommended cropping choice and management, (4) line charts displaying the monthly required work load, monthly manure storage levels, as well as profits at observed historic yields and prices for the last ten years, and finally (5) a map showing the spatial allocation of the different crops and the manure allocation.

Figure 2: Exemplary results page of the Fruchtfolge DSS (translated)



2.6 *Data adjustment and individualization*

Following the optimization, users are given two options of adjusting the optimization results. First, they may change the crop, manure application, catch crop, autumn fertilization, or N-reduction levels post simulation in the results page. When the user selects e.g. a different crop for a field, the results page is updated immediately, and a new info box is displayed. The info box will show the difference between the former optimized total contribution margin and the one reflecting the user's change. Note that an increase against the optimized total contribution margin is only possible if some constraint is violated. In that case, warnings show these violations, for instance exceeding maximal cropping shares or non-compliance with a measure from the FO. Hence, users can quickly perform 'what-if' scenarios and compare them with the optimization results. Providing the possibility of an ad-hoc sensitivity analysis aims to increase credibility in the DSS, and to reduce the black-box character of the underlying linear programming approach.

As a second adjustment option, users may alter the input data for the model. Opposed to the post simulation changes described before, changes to the input data are reflected in subsequent optimization runs. As previously stated, all the automatically acquired data can be changed. To give an example, users may add or remove fields, alter their geometries, change previous crops or mineralized nitrogen (N_{min}) contents. Regarding the crops, expected prices, yields, costs, maximum crop shares, labor requirements and previous crop effects can be adapted to the user's needs. In addition, fertilizing planning data such as target nitrogen amounts, manure nutrient contents, maximum manure application rates, and mineral fertilizer equivalents of manure can be changed.

3 Case study

In order to test the DSS and to illustrate its capabilities of finding the optimal crop and management choices in a complex environment, a hypothetical case study farm is generated. It is assumed to be located in the Borken region within the federal state of North Rhine-Westphalia, known for intensive livestock (mainly pig fattening) production (LWK NRW, 2014). The case study farm is assessed under varying policies, the FO 2017 as well as the FO 2020. The FO consists of numerous, partly interlinked measures which restrict the fertilizer management of farmers. The FO 2020 adds to the former version mainly additional restrictions in 'red' areas in which nitrate concentration targets are exceeded (see following section 3.1).

For the case study, three scenarios are modeled (see Table 3). The reference scenario (FULL-OPT-17) optimizes a cropping plan and fertilizing strategy under the FO 2017. It serves as a benchmark to calculate changes provoked by the FO 2020 as reflected in two additional scenarios. The first of these introduces the stricter obligations of the FO 2020 and evaluates their effect under the field specific cropping choice of the reference scenario. It is called FERT-OPT-20 as it only optimally adjusts the fertilization strategy to comply with new FO legislation but not the cropping plan. In the third scenario (FULL-OPT-20), Fruchtfolge finds the optimal cropping plan adaptation strategy under the proposed FO 2020 which minimizes compliance costs considering both changes in cropping choices and manure applications. All three scenarios use the same prices, yields as well as previous crops on each of the fields. Manure quantities not applied on the farm have to be exported and the related costs are added to the objective. Manure export costs of 12 € per m^3 are assumed (Kuhn et al., 2019). The scenarios under FO 2020 are further differentiated by considering different shares of fields being situated in a red area.

Table 3: Schematic overview of the scenario setup for the case study

Scenario	*Description*	*Fertilization Ordinance*	*Farmland in 'red' area*
FULL-OPT-17	Full optimization	2017	0%
FERT-OPT-20	Crop to field allocation fixed to reference scenario Fertilization strategy optimally adjusted to new Fertilization Ordinance	2020	0%, 50%, 100%
FULL-OPT-20	Full optimization	2020	0%, 50%, 100%

3.1 *German Fertilization Ordinance 2017 and 2020*

The FO implements the Nitrates Directive in Germany and was revised in 2017 after water quality benchmarks have been missed. The EU commission however sees the measures of the FO 2017 as insufficient to reach the environmental goals related to nitrate in ground and surface waters (Agra-Europe, 2019). Therefore, the FO has been anew revised in 2020 comprising distinct stricter measures (see

Table 4).

Table 4: Overview on core changes from Fertilization Ordinance 2017 (BMEL, 2017) to 2020 (BMEL, 2020)

	Fertilization Ordinance 2017	*Fertilization Ordinance 2020*	
	General changes	General changes	Additional restrictions in 'red' areas
Nutrient balance	Obligatory soil surface balance, surplus restricted	Nutrient balance abolished	-
Manure application	Limited to 170 kg N (nitrogen) ha^{-1} a^{-1}		Restriction applies at field instead of farm level

Fertilizing activities	Obligatory and predefined fertilizing planning based on N and P_2O_5 (phosphate) plant needs Only 10% of the autumn fertilization needs to be accounted for in the fertilizing planning calculation of the following year	Obligatory fertilizing planning and recording of every fertilizer application. Autumn fertilization has to be fully accounted for in the fertilizing planning calculation of the following year Minimum fertilizer efficiency coefficients for manure increased	-
Fertilizing restriction	Calculated plant need must not be exceeded	Minimum fertilizer efficiency coefficients for manure increased	Calculated plant need has to be undercut by 20%
Banning periods	Winter rape, winter barley, and catch crops can be fertilized in autumn with up to 60 kg N ha^{-1} a^{-1}	-	Winter rape, winter barley, and catch crops forbidden to fertilize in autumn
Catch crops	-	-	Obligatory catch crop cultivation for allowance of fertilizer application to following summer crops

The FO consists of numerous, partly interlinked measures. Most changes from the FO 2017 to the FO 2020 are linked to so-called ‘red’ areas, which describe areas above groundwater bodies exceeding the target nitrate concentration or showing increasing trends. Already under the Fertilization Ordinance 2017, farmers had to fulfil additional measures in ‘red’ areas which were however little restrictive and not relevant for the assessed decision problem (see Kuhn (2017) for detailed description of Fertilization Ordinance 2017).

In the FO 2020, a prescribed and detailed fertilizing planning approach plays a major role and replaces former restrictions on nutrient surpluses. The fertilizer application, covered by manure or mineral fertilizer, is constrained based on each crop’s need after subtracting different nutrient sources such as spring mineralization. The plant need is lowered by 20% for fields in ‘red’ areas, resulting in reduced fertilizer application. This reduction however applies in average on the affected fields, only, allowing for complex shifting between crops. Furthermore, the application of manure is restricted to 170 kg N (ha^{-1} a^{-1}, a threshold calculated at farm average under the FO 2017 and 2020. In ‘red’ areas, however, the threshold has to be met at field level. In addition, the mineral fertilizer equivalents of manure are increased in the fertilizing planning in the FO 2020. Finally, nitrate leaching in autumn should be reduced by the banning of fertilizer application to rape seed, winter barley and catch crops in spring as well as the obligatory catch crop cultivation before summer crops in the 'red' areas.

The measures of the FO 2020 render decisions on cropping choices and fertilizing more complicated. The described thresholds are added to the optimization process described in section 2.3. Also, the temporal limitations of fertilizer application are introduced as additional restrictions, returning the farm's optimal gross margin when meeting the requirements of the FO. The DSS thereby addresses the decision farmers have to take in the light of the stricter regulations of the FO 2020 such as (1) the adaption of cropping choice and fertilizer allocation inside and outside read areas, taking into account that N yield responses differ between crops, (2) the change of manure allocation on farm and manure export due to stricter application thresholds and banning of application in autumn, and (3) the economic assessment of summer crops due to costly obligatory catch crop cultivation.

3.2 *Case study farm characteristics*

To assess impacts of this spatially differentiated fertilizing restriction, the case study farm is given arbitrary 10 fields inside and 10 fields outside of a nitrate sensitive 'red' area in our medium scenarios. While the 20 fields are chosen arbitrarily for this case study, their shapes, previous crops, soil type, and quality correspond to actual fields. In total, the farm cultivates approx. 100 ha with an average field size of 5.6 ha outside and of 4.2 ha inside of the 'red' areas boundaries. Due to the shape of the 'red' area, the average field-to-farm distance is only 2 km for the fields inside and 6 km outside of it. Soil qualities and types are rather homogenous among the fields, with an average soil quality rating (Mueller et al. (2014)) of 64 inside and 57 outside of the 'red' areas boundaries. As discussed in section 2.3, regional crop yields, prices and direct costs were obtained from the KTBL-SGM database (KTBL, 2019). In the underlying assessment, the 10-year average of these values is considered as expected values for the planning period. N_{min} values for the fields are obtained from the North Rhine-Westphalian chamber of agriculture (LWK NRW, 2020a). To prohibit the generation of cropping plans that exceed the available labor endowment, peak labor constraints based on the previous year's cropping plans are introduced.

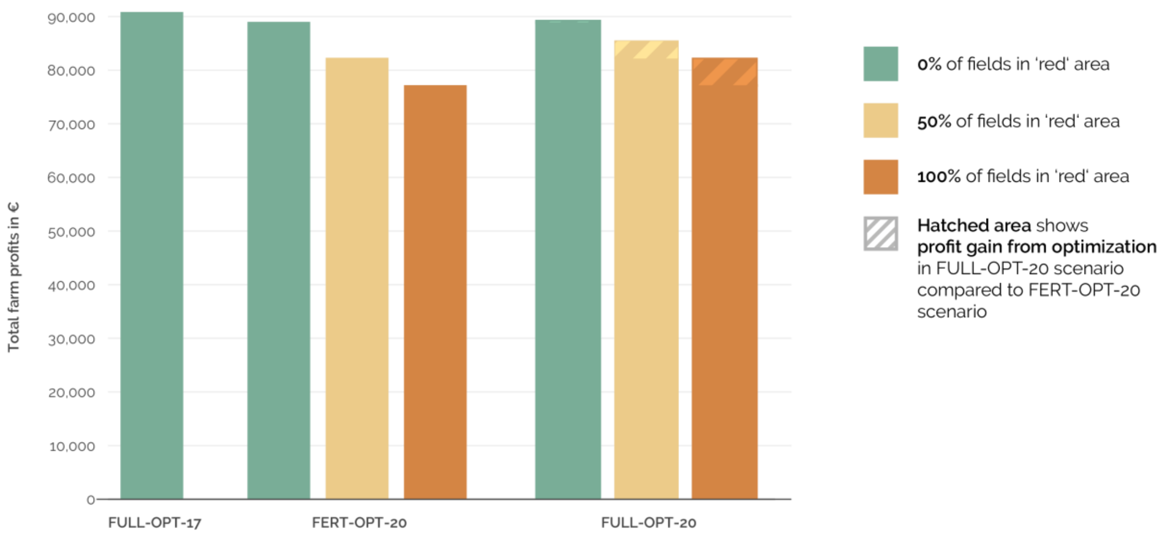
As previously stated, the case study farm is located in the livestock intensive region of Borken, Germany. The case study farm is given 2,000 pig fattening places which reflects the average in the region (Kreis Borken, 2020). It is assumed that the pigs are fattened using feed with reduced nitrogen and phosphate content (LWK NRW, 2018). Furthermore, a higher mineral fertilizer equivalent of 72% of the pig manure (compared to 60% stated in the FO) is assumed for the fertilizing planning, as suggested by planning data from the North Rhine-Westphalian chamber of agriculture (LWK NRW, 2020b). Due to the longstanding manure use in the area, N-target values are adapted accordingly (agrarheute, 2015).

The scenarios presented in Table 3 present different assumption on where fields are located: First, it is assumed that none of the fields are within a ‘red’ area. Second, half of the fields are in- and outside of the ‘red’ areas boundaries (reflecting the currently proposed boundaries). Third, all of the case study farms fields are simulated to be in a ‘red’ area. While the concept of ‘red’ areas has already existed in the FO 2017, the additional measures only included slightly stricter measures (BMEL, 2017). The varying size of the red area is therefore not included for the scenario FULL-OPT-17.

3.3 *Case study results*

For the given case study, we find profit losses induced by the stricter measures of the FO 2020 to vary largely depending on how many fields are situated in the ‘red area’. The losses range between 1,500 € and 13,650 € for the given case study farm. By following Fruchtfolge’s recommended cropping choices and fertilization strategies, the losses can be reduced by up to 4,700 € (see Figure 3).

Figure 3: Total farm profits of the different scenarios depending on the share of fields in a ‘red’ area



Under the FULL-OPT-17 scenario, the farm has a simulated profit of 90,506 € and faces manure export costs of 3,635 €. The farm grows maize on 44%, winter wheat on 18%, sugar beets on 20%, and potatoes on 17% of its land (Table 5). The farm cultivates about 26 ha of catch crops before seeding maize which allows to spread almost all available manure in autumn to avoid costly manure exports in this period.

In the FERT-OPT-20 scenarios, cropping choices are fixed to the results of FULL-OPT-17 scenario. This isolates the effects of the revised FO on the profit maximal fertilizing strategy and excludes the optimization of the cropping choices as a core feature of Fruchtfolge. The identical cropping plans of the FERT-OPT-20 and FULL-OPT-17 scenarios are displayed in the upper part of

Figure 4. Under the FO 2020, instead of 10%, now 100% of the nitrogen applied in autumn must be accounted for in the next year (see

Table 4). Using catch crops to enable autumn fertilization of maize is no longer economically attractive. If no fields are located in a 'red' area, growing of catch crops is reduced to the point where it just fulfills the 5% minimum ecological focus area obligation under the Common Agricultural Policy. While this saves costs for catch crop cultivation, the manure not spread in autumn must be exported instead, leading to a net loss in profit of 1,591 € (-1.76% compared to the reference).

In the case of 50% of the case study farms fields being in a 'red' area, net profit loss increases to 8,850 € (-9.78% compared to the reference), driven mainly by two of the FO 2020 measures in 'red' areas. First catch crop cultivation is now mandatory before growing a summer crop such as maize and sugar beet. As maize and sugar beets may not be fertilized with manure in autumn under the FO 2020 obligations, manure exports in autumn increase. Second, the requirement to reduce the calculated plant need for nitrogen by an average of 20% reduces both crop yields and the total amount of manure which can be spread. While the yield loss leads to diminishing revenues, the reduced amount of manure that can be spread is additionally driving up manure export costs. These effects are amplified in the scenario where 100% of the case study farms fields are in a 'red' area: the net loss in profit is further increased to 13,658 € (-15.09% compared to the reference).

In the FULL-OPT-20 scenarios, cropping choices as well as manure allocation are optimized, illustrating the full potential of Fruchtfolge. In the simulation run where no fields are situated in a 'red' area, the farm can increase its profits by 188 € compared to the FERT-OPT-20 with no fields in the 'red' area. The profit increase is realized by an increase in the maize share at the expense of the wheat share (Table 5). As in the FERT-OPT-20 scenario with no fields in a 'red' area, autumn fertilization and related catch crop cultivation are completely abandoned. Giving up catch crop cultivation to a large degree and shifting manure application partly to spring frees labor in a peak period in autumn and allows for slightly increasing the maize share. While the expected gross margin for potatoes is higher than the one for maize, the freed labor allows for a higher return when the maize share is increased. This can be explained by the relatively high labor requirement of the potatoes, which (on average) require about 36 h/ha in autumn compared to 7.3 h/ha in maize.

In the FULL-OPT-20 simulation run where 50% of the fields are situated in a 'red' area, Fruchtfolge is able to increases the farms profits by 3,204 € compared to the respective simulation run in the FERT-OPT-20 scenario. The profit gain is realized by decreasing the maize share and expanding wheat and potato cultivation (see middle panel of Figure 4). These profit maximal adjustments reflect several interactions between crops due to labor constraints as well as subtle impacts of changes in the FO. This favors an expansion of wheat in 'red' areas as the farmer can apply more manure without exceeding application limits and avoid costly manure exports. Furthermore, in opposite to maize and potatoes as summer crops, wheat does not face costs of mandatory catch crop cultivation in a 'red' area of around 105 €/ha. Additionally, expanding the wheat share frees labor which can be used to increase potato cultivation.

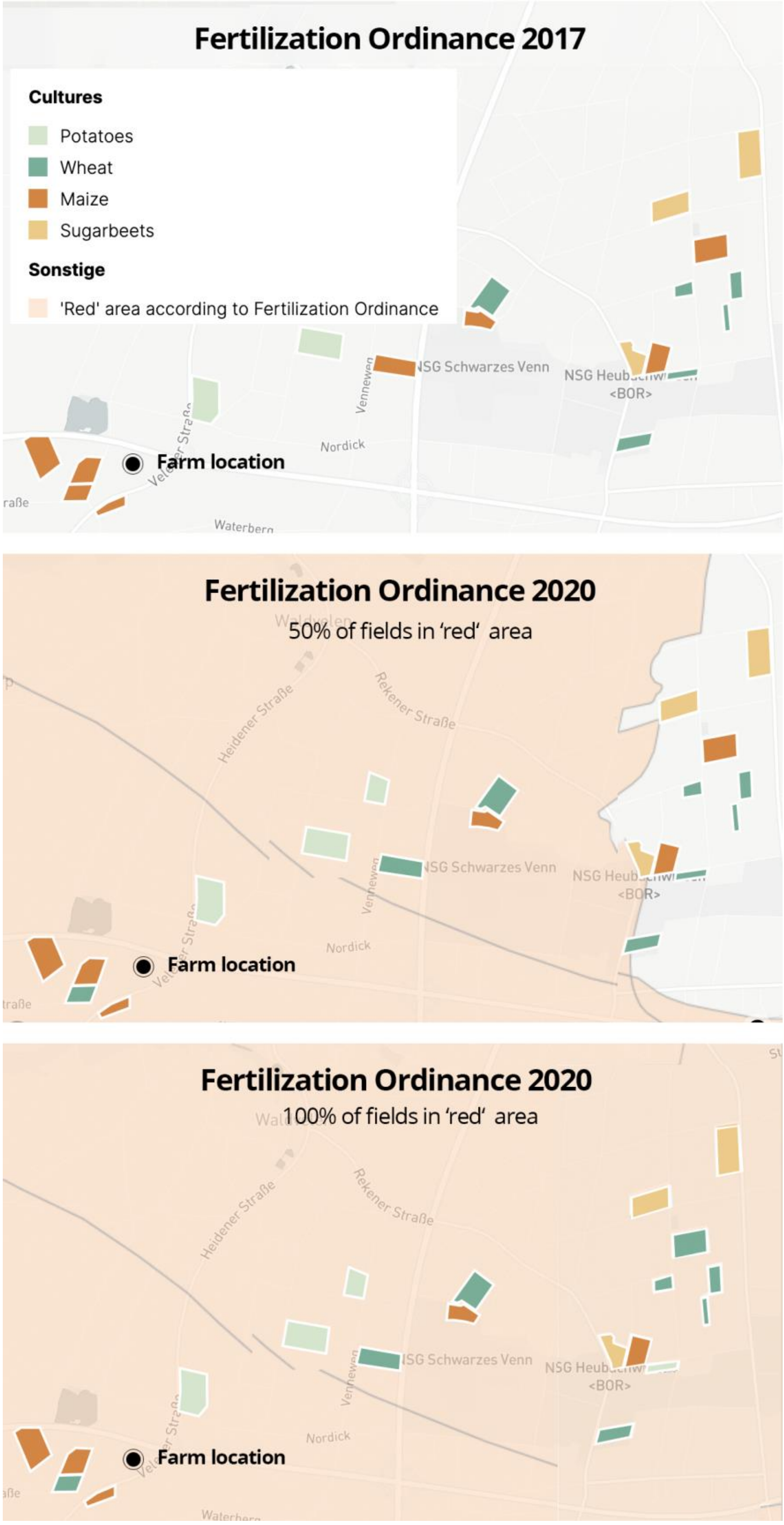
In the FULL-OPT-20 simulation run where 100% of the fields are situated in a ‘red’ area, a profit increase of 4,710 € is realized by Fruchtfolge when compared to the same simulation run in the FERT-OPT-20 scenario. Similar to the simulation run with 50% of the fields in a ‘red’ area, the farm further decreases its maize share, and increases wheat and potato shares to their maximal shares at farm level (see bottom panel of Figure 4).

The top of the image is showing the optimal cropping plan under the FO 2017 (reference and FERT-OPT scenarios), the middle panel the optimal cropping plan under the FO 2020 with 50% of the fields in a ‘red’ area (FULL-OPT), and the bottom panel the optimized cropping plan with 100% of the fields in a red area (FULL-OPT).

Table 5: Optimal crop shares resulting from the optimization for the Reference and OPT scenario given different shares of fields in a ‘red’ area

Scenarios	*Fertilisation Ordinance*	*Fields in 'red' area [%]*	*Maize*	*Wheat*	*Sugarbeet*	*Potatoes*
Reference / FERT-OPT	2017 / 2020	0%, 50%, 100%	44%	18%	20%	18%
FULL-OPT	2020	0%	45%	17%	20%	18%
FULL-OPT	2020	50%	30%	28%	20%	22%
FULL-OPT	2020	100%	24%	32%	20%	24%

Figure 4: Optimized cropping plans as resulting from the Fruchtfolge DSS for the case study farm



4 Discussion

4.1 *Scope and technical implementation of Fruchtfolge*

The Fruchtfolge DSS supports farmers both with proposals for optimal cropping choices as well as fertilization strategies in accordance with the revised German FO. This renders Fruchtfolge not only useful for arable farmers, but also for livestock farmers optimizing their manure allocation while ensuring that certain shares of arable land are used for fodder production.

While the automatic farm data import was solely available for the state of North Rhine-Westphalia in Germany at the time of writing, future versions of the Fruchtfolge DSS will include automatic data import for all federal states of Germany, and possibly other countries as well. This feature is made publicly available by the *harmonie*[4] software package, which harmonizes farm subsidy application files across (federal) boundaries.

To the best of our knowledge, Fruchtfolge is the first cropping choice DSS to follow principles of user centered design outlined by Rose (2017, 2016), considering features of established DSS such as the sustainable vineyard management DSS vite.net® (Rossi et al., 2014).

This relates to fully automated data collection which only requires users to provide their CRN to access EU direct payment applications of their farm for an initial optimization. A user-friendly and visually attractive interface eases the communication between the DSS and the user, shielding it from details of the underlying economic programming model. Similar to vite.net®, Fruchtfolge aims at assisting the decision-maker by making recommendations which can be quickly explored with regard to alternatives and their consequences. Finally, as highlighted by vite.net®, providing the DSS as a web application enables continuous updates by the provider, and flexible access for decision makers. All these elements aim at overcoming the often-observed underuse of DSS at farm-scale.

Fruchfolge captures a wide range of factors driving crop allocations to individual fields such as differences in gross margins, previous crop effects, minimal waiting times and restrictions related from command-and-control measures.

However, we deliberately do not expand Fruchfolge to cover diet optimization of animal herds and its interaction with optimal cropping choices. Far less automated data import is possible regarding the details of herd and, for instance, grass land management. Dynamics in livestock production and the inclusion of necessary intra-annual management options introduce numerous new aspects in the decision problem and require much more reflection on farm specifics.

[4] Hosted at https://github.com/fruchtfolge/harmonie

Interactions with farmers and advisors revealed that constraints on minimal feed crop shares captured in Fruchtfolge are deemed as transparent and sufficient for a DSS with a focus on crop allocation and manure management.

Providing tools which help to understand why a certain solution of a larger programming model is economically optimal remains a challenge.

Fruchtfolge offers different views on the results (Figure 2) which also highlight interactions between cropping choices. It allows “challenging” the optimal solution and exploring consequences of alternative ones. Infeasible solutions, e.g. when choosing a crop and a field that would surpass a labor constraint for a certain month, are avoided by the introduction of slack variables with high penalties. Still, the optimal solution to the mixed integer problem underlying the Fruchtfolge DSS might remain a black box to some degree, which can undermine the trust of users in the DSS (Jakku et al., 2019). Further interviews with users can research this point and identify additional options for result analysis or automated support.

4.2 *Case study results*

The case study farm can increase its profits by 180 € up to 4,710 € by using the Fruchtfolge DSS when compared to an unchanged crop allocation reflecting the restrictions from the previous FO 2017. Increases in real world-cases are most likely considerably higher as users will also improve their crop and manure allocation at the benchmark (Mußhoff and Hirschauer, 2006b). The profit increases certainly outweigh the costs for the approx. 5 minutes of time required for a first optimal solution already tuned to farm specifics.

The announcements of the stricter measures outlined in the FO 2020 lead to nationwide protests from farmers in Germany, as reported in the media (Daily Mail, 2019). Due to Fruchtfolge’s ability to outline a cost minimal compliance strategy for the FO 2020, the DSS may help to increase the acceptance of the stricter measures.

The case study highlights key drivers of farm-level impacts of the FO 2020. Compliance costs can be considerable and strongly depend on the share of farmland in ‘red’ areas. Therefore, our tool is shown to be of particular interest for farmers and farm advisers managing fields in such a ‘red’ area.

For the analysis, it was assumed that labor use should not exceed the labor use of the previous year’s cropping plans. We found that the marginal profitability of an additional hour of labor in September could reach up to around 90 €. Case study results are hence rather sensitive to the available labor endowment in autumn. In interactive use, a farmer would probably allow for higher labor input in this period. This underlines the usefulness of interactive data updates and also points at new possibilities to exploit the dual solution as well to develop recommendations in future releases.

As previously stated, the assumed reduced N-requirements of the crops reflect long-standing manure fertilization present in the case study. This assumption dampens yield reductions and profit impacts of the required 20% reduction of nitrogen fertilizer application in a ‘red’ area. Given less efficient fertilizer management, optimization gains realized by Fruchtfolge will be higher. Note that all fertilizing parameters can be interactively adjusted in Fruchtfolge (section 2.6) in order to precisely reflect farm characteristics and famer’s preferences.

Similar to the findings of Kuhn et al. (2019), our results including compliance cost are quite sensitive to parameters related to fertilizer use. In this regard, literature finds strong efficiency differences in farm samples (LWK NRW, 2018; Osterburg and Techen, 2012) which can only partly be related to farm type and locational factors such as soil and climate. Compliance costs with the FO 2020 will therefore differ across farms as well as potential benefits from using Fruchtfolge. Both also depend on the assumed manure export costs as to some degree manure export is a central compliance strategy to the FO 2020. The costs chosen in the case study reflect current conditions for manure exports such as average transport distances. However, some cost increases are likely under the FO 2020 as many German livestock farms will need to expand exports, driving up transport distances and thus costs. Both the assumed high fertilizing efficiency in the case study and using current manure export cost render the reported compliance costs rather lower limits for actual ones in our case study farm. Again, the possibility to interactively change these assumptions in the DSS renders Fruchtfolge useful for evaluating possible impacts of higher manure exports costs on a particular farm.

4.3 *Implementation in practical use*

Musshoff and Hirschauer (2016) state that despite ongoing research efforts, mathematical programming methods have barely been adopted by farmers and farm advisers in Germany. As one of the main reasons, they argue that high data requirements impede the adoption of DSS using mathematical programming. Incorporating automation in data collection, following best practices of user centered design and lessons learned from established DSS, Fruchtfolge aims to overcome this implementation gap.

Our case study underlines the usefulness of applying a constrained optimization framework to determine which crop to grow on which field and how to fertilize it, especially in the light of a complex regulatory environment. Farmers may use “Fruchtfolge” to identify optimized production alternatives to their current production program which comply with the updated legislation and reflect manifold farm and field specific characteristic and restrictions. “Fruchtfolge” thus helps farmers to minimize compliance cost for the newest revision of the FO 2020. Also, Fruchtfolge helps farmers to avoid penalties due to accidental violations against legal frameworks, as the optimized cropping plan will automatically adhere to them and will warn farmers about violations.

Ongoing tests of the DSS with farmers are promising. Especially younger farmers (digital natives) show a high acceptance. Future research should evaluate the usefulness, design, and eventually the adoption of the Fruchtfolge DSS with farmers and lead the further development of the application. Multiple extensions to the current functionality are possible: future versions of the DSS could for example help farmers evaluate the profitability of agri-environmental measures on their farm, and thus improve the environmental footprint of the farm while increasing income. At present, the German agricultural administration digitizes reporting obligations and services for farmers. This process offers the chance to link DSS like Fruchtfolge to existing and widely-used digital platforms, and thereby promote the use of DSS in farming.

5 Conclusion

The Fruchtfolge DSS provides farmers with an economically optimal cropping and fertilizing plan without the need of time-consuming data input. In our case study, profit gains ranging from 180 € up to 4,710 € can be realized by using the DSS. Fruchtfolge reflects various legal constraints and thus helps farms to comply with the new FO in a cost minimal way. Due to its flexibility and design, farmers can easily carry out what-if scenarios and challenge the results of the underlying mathematical optimization model. This allows for "informed decisions" about alternative cropping and fertilizer management choices based on the economic, agronomic, and legal consequences compared to the optimized plan proposed by the DSS. Incorporating experiences from the literature about best practices in the design and implementation of a DSS, Fruchtfolge offers an attractive user interface and fast response times to overcome the "implementation gap" often prevalent with other DSS. With the increasing availability of site-specific sensor data, Fruchtfolge can be enhanced to incorporate even higher detailed farm specific data without requiring additional user interaction. Fruchtfolge is free and open source, and welcomes contributions to its codebase and documentation.

6 Acknowledgements

This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2070 – 390732324.

Supplementary materials

See supplementary material file.

References

Acutis, M., Alfieri, L., Giussani, A., Provolo, G., Guardo, A.D., Colombini, S., Bertoncini, G., Castelnuovo, M., Sali, G., Moschini, M., Sanna, M., Perego, A., Carozzi, M., Chiodini, M.E., Fumagalli, M., 2014. ValorE: An integrated and GIS-based decision support system for livestock manure management in the Lombardy region (northern Italy). Land Use Policy 41, 149–162. https://doi.org/10.1016/j.landusepol.2014.05.007

Agra-Europe, 2019. Kommission zwingt Deutschland zur Nachbesserung bei der Düngeverordnung. Agra-Europe 6, 35–36.

agrarheute, 2015. Stickstoffdüngung: So finden Sie die richtige Menge [WWW Document]. agrarheute. URL https://www.agrarheute.com/pflanze/stickstoffduengung-so-finden-richtige-menge-442024 (accessed 4.22.20).

BGR, 2016. Ackerbauliches Ertragspotential der Böden in Deutschland. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). [WWW Document]. URL http://www.bgr.bund.de/DE/Themen/Boden/Ressourcenbewertung-management/Ertragspotential/Ertragspotential_node.html (accessed 1.22.17).

Bitkom, 2020. Schon 8 von 10 Landwirten setzen auf digitale Technologien. Bitkom (e.V.). [WWW Document]. URL https://www.bitkom.org/Presse/Presseinformation/Schon-8-von-10-Landwirten-setzen-auf-digitale-Technologien (accessed 5.6.20).

BMEL, 2020. Verordnung zur Änderung der Düngeverordnung und anderer Vorschriften. Federal Ministry of Food and Agriculture (BMEL). [WWW Document]. URL https://www.bundesrat.de/SharedDocs/drucksachen/2020/0001-0100/98-20.pdf?__blob=publicationFile&v=2 (accessed 6.5.20).

BMEL, 2017. Verordnung zur Neuordnung der guten fachlichen Praxis beim Düngen. Federal Ministry of Food and Agriculture (BMEL) [WWW Document]. URL https://www.bundesrat.de/SharedDocs/drucksachen/2017/0101-0200/148-17.pdf?__blob=publicationFile&v=9 (accessed 5.6.20).

Britz, W., 2014. A New Graphical User Interface Generator for Economic Models and its Comparison to Existing Approaches [WWW Document]. German Journal of Agricultural Economics. https://doi.org/ISSN 0002-1121

Daily Mail, 2019. 10,000 farmers descend upon Berlin [WWW Document]. Mail Online. URL https://www.dailymail.co.uk/news/article-7727755/10-000-farmers-descend-Berlin.html (accessed 5.15.20).

Galán-Martín, Á., Pozo, C., Guillén-Gosálbez, G., Antón Vallejo, A., Jiménez Esteller, L., 2015. Multi-stage linear programming model for optimizing cropping plan decisions under the new Common Agricultural Policy. Land Use Policy 48, 515–524. https://doi.org/10.1016/j.landusepol.2015.06.022

GAMS Development Corporation, 2019. General Algebraic Modeling System (GAMS) Release 27.1.0.

Hazell, P.B.R., Norton, R.D., 1986. Mathematical programming for economic analysis in agriculture. Macmillan, New York.

Heyn, J., Olfs, H.-W., 2018. Wirkungen reduzierter N-Düngung auf Produktivität, Bodenfruchtbarkeit und N-Austragsgefährdung - Beurteilung anhand mehrjähriger Feldversuche, VDLUFA-Schriftenreihe. VDLUFA-Verlag, Darmstadt.

IBM ILOG CPLEX, 2009. V12. 1: User's manual for CPLEX. International Business Machines Corporation 46, 157.

Jakku, E., Taylor, B., Fleming, A., Mason, C., Fielke, S., Sounness, C., Thorburn, P., 2019. "If they don't tell us what they do with it, why would we trust them?" Trust, transparency and benefit-sharing in Smart Farming. NJAS - Wageningen Journal of Life Sciences 90–91, 100285. https://doi.org/10.1016/j.njas.2018.11.002

Kreis Borken, 2020. STATISTIKATLAS [WWW Document]. URL https://kreis-borken.de/fileadmin/kbor/FB_15/Statistik/Statistikatlas/atlas.html (accessed 2.4.20).

KTBL, 2019. Standard gross margins [WWW Document]. URL https://daten.ktbl.de/sdb/welcome.do (accessed 6.17.19).

KTBL, 2018. Betriebsplanung Landwirtschaft 2018/19 Daten für die Betriebsplanung in der Landwirtschaft. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt.

Kuhlmann, F., 2015. Landwirtschaftliche Standorttheorie: Landnutzung in Raum und Zeit, 1. Auflage. ed. DLG-Verlag, Frankfurt am Main.

Kuhn, Schäfer, Holm-Müller, Britz, 2019. On-farm compliance costs with the EU-Nitrates Directive: A modelling approach for specialized livestock production in northwest Germany. Agricultural Systems 173, 233–243. https://doi.org/10.1016/j.agsy.2019.02.017

Kuhn, T., 2017. The revision of the German Fertiliser Ordinance in 2017 (Discussion Paper No. 2), Discussion Paper. Universität Bonn, Bonn.

Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Lansink, A.O., Ittersum, M.V., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agricultural Systems 103, 585–597. https://doi.org/10.1016/j.agsy.2010.06.006

LWK NRW, 2020a. Nmin-Richtwerte für Winterungen 2020. Landwirtschaftskammer Nordrhein-Westfalen (LWK NRW). [WWW Document]. URL https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/duengung/basisinfos/nmin-winterungen.htm (accessed 3.30.20).

LWK NRW, 2020b. Düngen mit Wirtschaftsdüngern. Landwirtschaftskammer Nordrhein-Westfalen (LWK NRW). [WWW Document]. URL https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/duengung/duengeverordnung/wirtschaftsduenger.htm (accessed 3.30.20).

LWK NRW, 2018. Nährstoffbericht 2017 - Wirtschaftsdünger und andere organische Dünger. Chamber of Agriculture North Rhine-Westphalia (LWK NRW) [WWW Document]. URL www.landwirtschaftskammer.de/landwirtschaft/ackerbau/pdf/naehrstoffbericht-2017.pdf (accessed 5.11.20).

LWK NRW, 2014. Landwirtschaft im Münsterland Daten - Fakten - Analysen. Landwirtschaftskammer Nordrhein-Westfalen (LWK NRW).

McCarl, B.A., Candler, W.V., Doster, D.H., Robbins, P.R., 1977. Experiences with farmer oriented linear programming for crop planning. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 25, 17–30. https://doi.org/10.1111/j.1744-7976.1977.tb02862.x

Mueller, L., Schindler, U., Shepherd, T.G., Ball, B.C., Smolentseva, E., Pachikin, K., Hu, C., Hennings, V., Sheudshen, A.K., Behrendt, A., Eulenstein, F., Dannowski, R., 2014. The Muencheberg Soil Quality Rating for Assessing the Quality of Global Farmland, in: Mueller, L., Saparov, A., Lischeid, G. (Eds.), Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia, Environmental Science and Engineering. Springer International Publishing, Cham, pp. 235–248. https://doi.org/10.1007/978-3-319-01017-5_13

MULNV, 2020. ELWAS Web [WWW Document]. URL https://www.elwasweb.nrw.de/elwas-web/index.jsf (accessed 2.4.20).

Mußhoff, O., Hirschauer, N., 2016. Modernes Agrarmanagement: betriebswirtschaftliche Analyse- und Planungsverfahren, 4., überarbeitete und erweiterte Auflage. ed. Verlag Franz Vahlen, München.

Mußhoff, O., Hirschauer, N., 2006a. Die Rehabilitation von Optimierungsverfahren? -Eine Analyse des Anbauverhaltens ausgewählter Brandenburger Markt- fruchtbetriebe. Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V. 495–507.

Mußhoff, O., Hirschauer, N., 2006b. Wie viel bringt eine verbesserte Produktionsprogrammplanung auf der Grundlage einer systematischen Auswertung empirischer Zeitreihen? Agrarwirtschaft 55, 175–187.

Mußhoff, O., Hirschauer, N., 2004. Optimierung unter Unsicherheit mit Hilfe stochastischer Simulation und Genetischer Algorithmen. Agrarwirtschaft 53, 264–279.

Osterburg, Techen, 2012. Evaluierung der Düngeverordnung – Ergebnisse und Optionen zur Weiterentwicklung (Abschlussbericht). National Working Group for the Evaluation of the Fertilization, Braunschweig.

Parker, C., Sinclair, M., 2001. User-centred design does make a difference. The case of decision support systems in crop production. Behaviour & Information Technology 20, 449–460. https://doi.org/10.1080/01449290110089570

Radulescu, C.Z., Radulescu, M., 2012. A Decision Support Tool Based on a Portfolio Selection Model for Crop Planning under Risk. Studies in Informatics and Control 21, 377–382. https://doi.org/10.24846/v21i4y201203

Rose, D.C., Parker, C., Fodey, J., Park, C., Sutherland, W.J., Dicks, L.V., 2017. Involving stakeholders in agricultural decision support systems: Improving user-centred design. International Journal of Agricultural Management 6, 10. https://doi.org/10.5836/ijam/2017-06-80

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: Towards effective design and delivery. Agricultural Systems 149, 165–174. https://doi.org/10.1016/j.agsy.2016.09.009

Rossi, V., Salinari, F., Poni, S., Caffi, T., Bettati, T., 2014. Addressing the implementation problem in agricultural decision support systems: the example of vite.net®. Computers and Electronics in Agriculture 100, 88–99. https://doi.org/10.1016/j.compag.2013.10.011

Schönhart, M., Schmid, E., Schneider, U.A., 2011. CropRota – A crop rotation model to support integrated land use assessments. European Journal of Agronomy 34, 263–277. https://doi.org/10.1016/j.eja.2011.02.004