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Crop rotation and management tools for every farmer? The current status on crop rotation and management tools for enabling sustainable agriculture worldwide

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ABSTRACT

Providing crop rotation and management (CRM) tools for every farmer worldwide might be the breakthrough in solving the UN sustainable development goal (SDG) of *zero hunger*. Evaluating whether available CRM software fits the needs of farmers worldwide, existing non-commercial CRM tools are categorized and benchmarked on several attributes like needed input data sources, needed minimum field sizes, provided optimization targets, adaptability to different farming regions, and intuitiveness of its graphical user interfaces (GUI). By focusing on the majority of worldwide farmers, which are small-scale, subsidiary, or smallholder farmers, the comparison of nowadays CRM software indicates that almost all tools are going to optimize the profit of the farming activity only, where only a few consider the reduction of fertilizer, the available amount of water, and other targets in the provided crop rotation plan. Further, all CRM tools neglected farms with only a few hundred square meters of farming ground. Based on the benchmark findings, needed research and implementation direction for CRM software are formulated, allowing farmers worldwide to use the benefits of crop rotation and management for tackling the SDG of *zero hunger*.

1. Introduction

Worldwide, every farmer has to decide which crops to plant when and in which field. Making these decisions leads to crop rotation planning. Crop rotation planning is, scientifically speaking, a highly complex optimization issue. For this optimization, weather, climate, farm size, available machinery, crops characteristics, and fields properties, including their soil characteristics, sizes, shape, and proximity to similar fields, needs, next to other values, to be considered. Next to the values influencing crop rotation, the optimization target, or the targets, also need to be defined [1–3].

Coping with changing weather, crop, and field conditions by the use of crop rotation is not new and even farmers centuries ago recognized that changing the kind of crops grown on the same field improves the yield and plants' health. The positive impacts of crop ration are also scientifically proven [2,4].

Therefore this paper will evaluate to what extent the existing crop rotation and management (CRM) tools are applicable for small-scale, i. e., smallholders, farms around the globe, and how they contribute to reaching the goals of the SDG of *zero hunger*. By doing so, Section 2 introduces the 17 UN SDG with the focus on the SDG of *zero hunger*. Section 3 disucsses the user and target groups to empathize with users using CRM tools, followed by a brief overview of CRM tools types in Section 4. Before comparing seven selected CRM for farmers in Section 6, Section 5 will introduce CRM and their basic elements summarized in Table 1. Combining all previous sections, Section 7 will comprise the results, reflecting whether every farmer worldwide can use current CRM tools. So that the, how CRM can contribute to reaching the goals of the SDG of *zero hunger* is discussed in Section 8.

Abbreviations: CRM, crop rotation and management; SDG, UN sustainable development goal; GUI, graphical user interfaces.

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2. UN sustainable goals

In 2015, the United Nations General Assembly set up 17 Sustainable Development Goals (SDGs), intended to be achieved by 2030. One of the 17 goals is *zero hunger* (SDG-2), intending to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" [5]. This goal addresses the problem that in 2019, an estimated 690 million people experienced hunger, two billion were affected by moderate or severe food insecurity, and 149.2 million children under five were suffering from stunting, i.e., low height for age [5]. SDG-2 highlights the inter-linkages between food security, nutrition, and sustainable agriculture. Extreme hunger and poverty are mainly rural problems, with smallholder farmers and their families making up a significant proportion of the poor and hungry [5]. The output in yield and earning per labor is more minor than large-scale producers, and so is the overall income.

According to SDG-2, agricultural production has to transform into a more sustainable, more productive, and less wasteful agrarian system. It has to sustainable use land, soil, water, and plant genetics. It has to boost yields through sustainability. It has to use wise management of scarce water, and it has to incorporate traditional farmers' knowledge combined with scientific farming knowledge. Concerning climate change, all of the above necessities become even more important, because of the rapid changes in temperature, precipitation, and pests. CRM tools might enable every farmer to broaden their knowledge in crop rotation planning to increase the yield without ruining fields, forests, veldt, etc.

Table 1
Comparison of the CRM tools focusing on the basic element: underlying algorithm, manual and automatic input data, data sources, and implementation type.

CRM Tool	Underlying Algorithm	Input Data (manual)	Input Data (automatic)	Data Sources	Platform
FruchtFolge [18]	• net-gross margins • mixed integer linear programming model	• ZIB-code • (optional) adjustments to every data point (fix/variable costs, crop rotation table, field characteristics etc.)	• farm and field locations • field characteristics (geometry and location) • soil characteristics • previous cultivated crops • regional historical yields and prices • crop management operations • fertilization restrictions • crop rotation table	• IACS • KTBL • BGR • OSM • ELWAS-WEB • CropRota	• web service • programming language: GAMS
FARMs [19]	• DSSAT	• field characteristics (geometry and location) • plants • irrigation • fertilization • tillage • expected harvest date	• in-season and historical weather data • soil data	• NASA POWER • Global High-Resolution Soil Profile database	• web service
LAMPs [20]	• similarity measures	• area of interest	• US states' borders • crop management zones • irrigation map • crop rotations (generic and observed) • crop management operations	• USGS • CropScape • LMOD	• web service
MORDMAgro [21]	• net-gross margins • DSSAT	• area of interest • cropping alternatives • soil parameters	• historical weather data • extreme weather events • historical crop prices • six predefined cropping alternatives • crop management operations	• Asociación Argentina de Consorcios Regionales de Experimentación Agrícola • weather station Junín Airport	• programming language: **R**
Peltonen-Sainio et al. [22]	• scoring system	• ZIB-code • (optional) adjustments (possible crops, rearrangement of crops)	• field characteristics (geometry and location) • crop rotation scores (crop rotations, sowing time, etc.) • previous cultivated crops • region specific crops	• Luke database • data from literature	• web service
Fendji et al. [23]	• mixed integer linear programming model	• crops • botanical family of specified crops • duration of crop • financial resources • field characteristics • soil characteristics	• regional historical yields and prices • generic crop rotation scores	• data from literature	• programming language: Julia • **no implementation published**
von Lücken et al. [24]	• evolutionary algorithms	• crops • botanical family of the specified crops • sowing and harvesting dates of crops • fixed costs of crops • nutrient balance of the crops (absorption and extraction) • field characteristic • soil characteristics	• regional historical yields and prices	• none	• **no implementation published**

3. User and target groups

Nowadays, CRM tools usually target large-scale commercial farms with huge investment potential and modern machinery. The costs of purchasing these tools are often beyond the possibilities of many small-scale, subsidiary, or smallholder farmers [6]. In low and lower-middle-income countries, which are most affected by the SGD-2 and mainly located in central Africa and Asia, cf. plot Fig. 1, small-scale farms make up the vast majority of all farms, owning most of the farmland, cf. plots Figs. 2 and 3. These farms are often run by the owner and their families with handed-down knowledge, but without vocational school instructions, powerful computer hardware, or other "bookish knowledge" [7]. Additionally, the use of CRM tools is still very limited among farmers [8–10]. Because of these barriers, a knowledge gap exists between small-scale farmers in developing counties on the one hand, and researchers and expert systems on the other [9]. Public sector programs have tried to overcome this gap by providing agriculture extension services, but these programs have not been widely adopted and are criticized broadly, because of their limited scale, sustainability, and impact [11].

Consequently, small-scale, subsidiary, or smallholder farmers, which have a high impact on the SGD-2, must be the target group for designing CRM tools, in order to overcome this knowledge gap. CRM tools, which implement knowledge from experts and researches, can increase the productivity of these farmers, without the need for high investments, like buying new land or new machinery [7]. Next to this, by using appropriate CRM tools, the income of these farmers might increase, and the sustainability of their farming actions will improve. With the global spread of mobile phones, these farmers most likely own a smartphone and are familiar with its handling [11]. By reflecting the whole user context, a CRM tool for this target group must abide to a user-centered designed. Rose et al. [12] proposed a list of 15 factors that need to be considered when designing a decision support system. We selected the six most important for the defined target group:

- Performance (appropriate function) does the tool perform a useful function and work well?
- Ease of use - is the user interface easy to navigate?
- Cost - is there a cost-benefit or is the initial cost too high?
- Habit - does the tool match closely with existing habits of farmers? / is the tool adaptable to the users needs and habits?
- IT education - does the tool require good IT skills to use?
- Facilitating conditions - can the tool be used effectively, i.e. is there the need of internet access? / does the tool fit farmer workflows? / does the tool provide explanations of the proposed actions to the farmer?

Considering these attributes, the requirements are that the CRM tools must provide an intuitive user interface (UI) using the spoken language as display language, supported by easily-understood pictures, icons, and video sequences and that the important parameters of the fields can be collected without the need of additional sensors. Thus, the data collection must use the farmer's interactive data input with the build-in smartphone sensors like camera, inertial measurement unit and GPS. To ensure that costs are not the prohibiting factor, the CRM should be free of charge. Furthermore, as cellular coverage may be limited [13], the CRM should be able to operate with limited network coverages. It must be adaptable to the individual farmers preferences and, most importantly, it must provide an appropriate function. The appropriateness of the tools function depends strongly on the individual farmers needs, it ranges from simple access to information, like the weather or market prices of the crops, to a complete cropping plan containing the spatial allocation, planting and harvesting dates, the overall workload etc. Thus, the tool must be easily adoptable to the individual farmers needs and preferences.

4. Types of crop rotation and management tools

Generally, a CRM tool supports the user in planning which crops to plant and how to manage them. Different types of CRM tools exist, depending on multiple aspects. The most important aspects to consider are the target group using these tools and the optimization target of the crop rotations—both are closely dependent on each other. Thus, CRM tools aim to optimize on different targets, e.g., increase the farm's net income, reduce the use of pesticides, or maximize the yield. Single objective CRM tools try to optimize on one target value, whereas in contrast, multi-objective tools optimize between several targets like the amount of fertilizer used, the accruing manure of the livestock, and the overall profit.

CRM tools are mostly tailored for occidental farmers as target groups, but some are tailored for scientists as well. Some CRM tools, like the Decision Support System for Agrotechnology Transfer (DSSAT) [16], can be used by users from different groups, while the majority are explicitly designed for one target group. Next to the target groups, the CRM tools differ in their underlying algorithms, i.e., the acquisition of the input

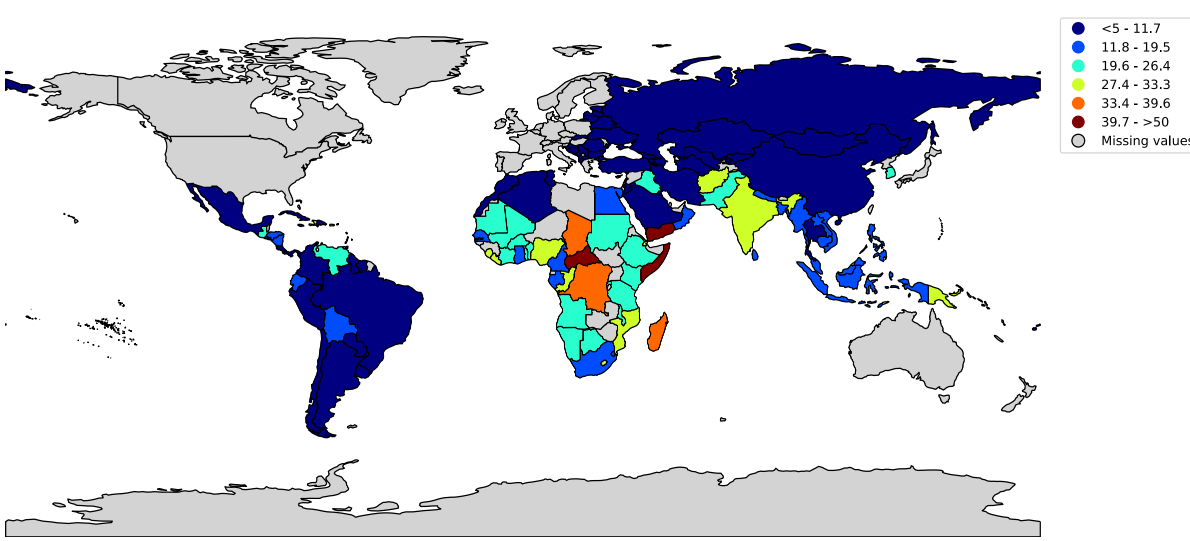
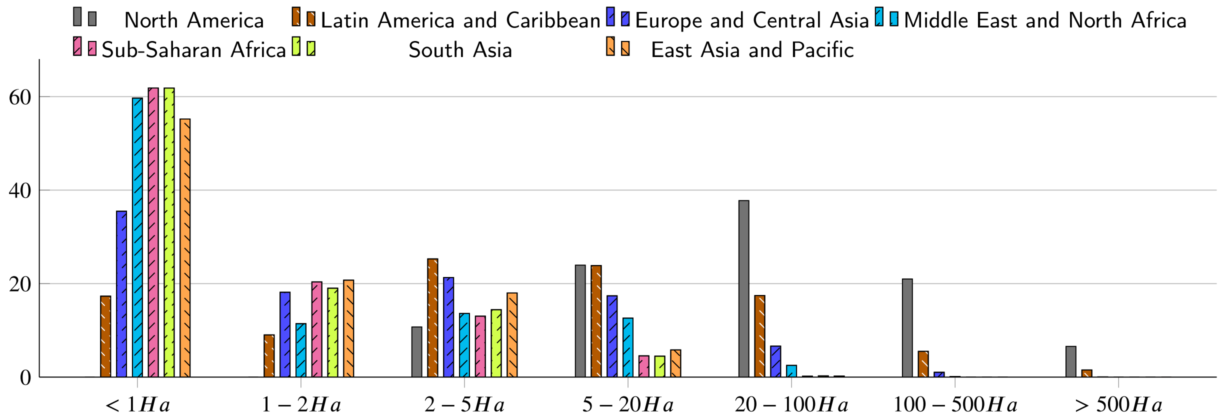
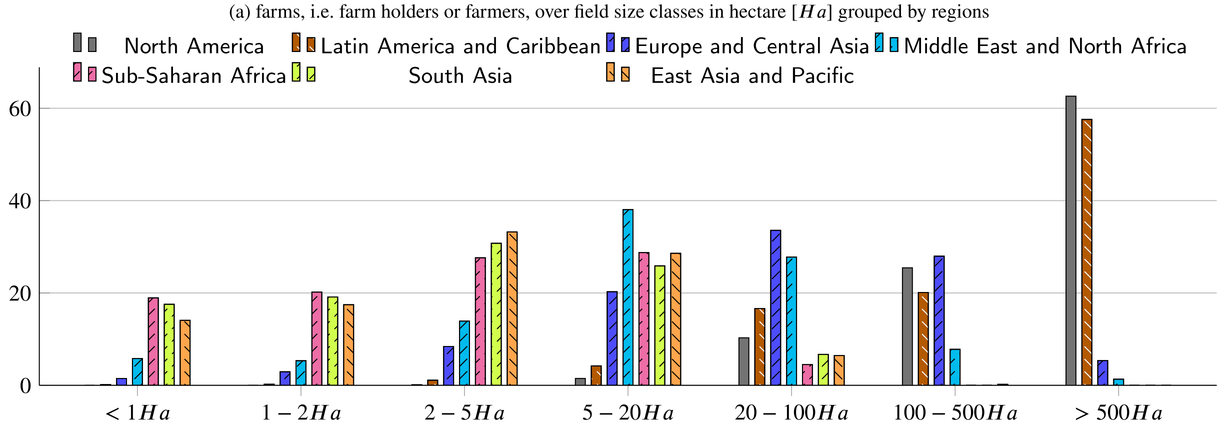


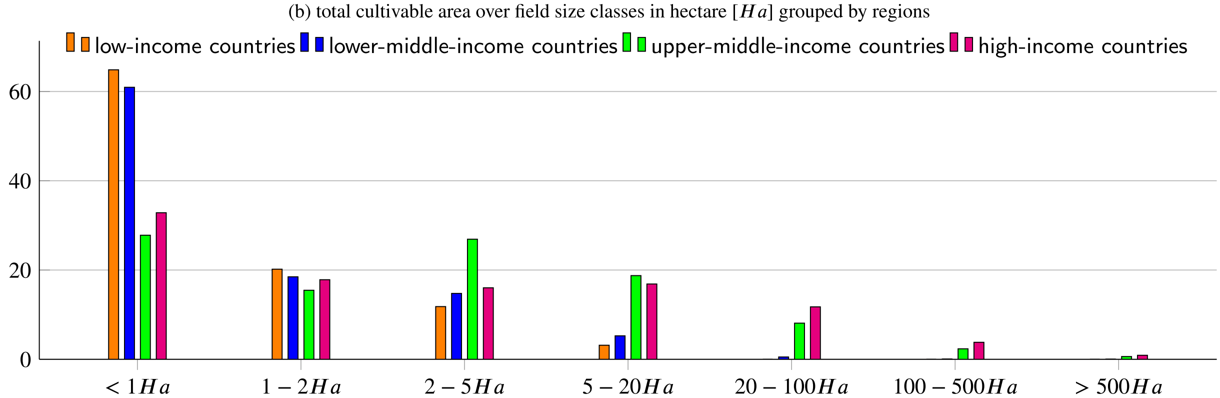
Fig. 1. World Hunger Map [14], the world hunger index is a numerical score based on several aspects of hunger as a multidimensional measure of national, regional, and global aspects.



(a) farms, i.e. farm holders or farmers, over field size classes in hectare [Ha] grouped by regions



(b) total cultivable area over field size classes in hectare [Ha] grouped by regions



(c) farms, i.e. farm holders or farmers, over field size classes in hectare [Ha] grouped by average fiscal income

Fig. 2. Distribution of farms and cultivable area over field size classes by regions and incomes; data source Lowder et al. [15].

data, the processing as well as the fusion of the data, the data visualization, the optimization method, and the user interaction. Especially the data processing and fusion of multiple data sources need sophisticated algorithms to produce a variety of propositions. Thus, depending on its type, CRM tools significantly differ in their optimization targets, complexity, software costs, computation costs, data acquisition methods, and visualization.

By focusing on *CRM tools for farmers* worldwide, cf. Section 3, *CRM tools for scientists* like the DSSAT and Agricultural Production Systems sIMulator (APSIM) [17] are not included in the remainder of this paper.

5. Crop rotation and management tools for farmers

Based on the target group farmers, seven CRM tools are selected for this evaluation and will be briefly summarized in this section. The first CRM included is the decision support system FruchtFolge by Pahmeyer et al. [18]. FruchtFolge follows the best practices of user-centered design by minimizing the required workload and relying heavily on automated data imports. A mixed-integer linear programming (MILP) model is used as the underlying algorithm.

The *Food, Agriculture, and Resource Management system* (FARMs) is a crop modeling application developed by Kim and Kisekka [19] at the University of California. FARMs is developed to simplify the crop simulation model DSSAT so that instead of scientists, farmers can apply it. For this reason, FARMs provides a simple form to be filled by the user, combined with an automated data import.

The *Land-use and Agricultural Management Practice web-Service* (LAMPs), developed by Kipka et al. [20] at the United States (US) department of agriculture, agriculture research service, links three different, US-based data sources. Database queries and string matching is used to generate crop rotations and management information.

González et al. [21] from the University of Argentina published the

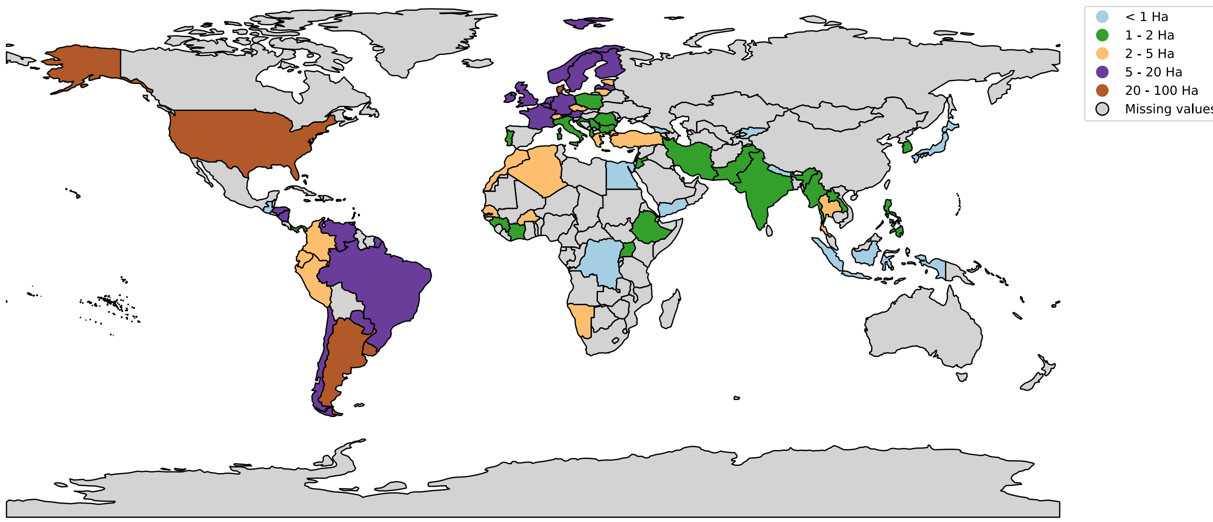


Fig. 3. Map of median field sizes per country; data source Lowder et al. [15].

Many Objective Robust Decision-making Model for Agriculture decisions (MORDMAgro). Based on historical data and expert knowledge, the model proposes multiple crop management options based on a simulation using DSSAT.

Peltonen-Sainio et al. [22] from the Natural Resources Institute Finland developed an *interactive tool for farmers to diversify high-latitude cereal-dominated crop rotations*. A scoring system is used to generate a crop rotation as diverse as possible, with all data used being automatically imported from different sources, together with the possibility of modifications by the user.

A collaboration of the university Ngaoundere, Cameroon, together with the University of Bremen by Fendji et al. [23] resulted in the *linear programming model for improving farmers revenue in crop rotation systems with plot adjacency constraints in organic farms with nutrient amendments*. A crop rotation plan is computed using a linear programming model, based on expert knowledge and data from different data sources. von Lücken et al. [24] published a model for the knowledge-based and intelligent engineering systems – intelligent decision technologies conference. This model uses five different evolutionary algorithms to generate a many-objective crop rotation plan.

5.1. Basic elements

CRM tools are based on several elements like the used algorithm, databases, and UI. This subsection describes the individual elements and how they are combined in the tool's design.

5.1.1. Crop rotation algorithm

The underlying algorithm of the CRM tool must be seen as their core function. Calculating an optimal crop rotation is a highly complex task, which depends on various factors, ranging from biological essentials to socioeconomic circumstances. The underlying algorithm defines how this is done. It integrates and evaluates the different data points to produce the desired output. It determines the accuracy and adaptability of the tool. Some tools integrate existing tools or formalized insights from research in this field, and others do all calculations from scratch.

Linear programming models are used in FruchtFolge [18] and Fendji et al. [23]. Both define constraints and goals as formulas that get maximized or minimized by a MILP solver.

FruchtFolge first calculates the gross margins for each field, i.e., the difference between revenue and the cost of goods sold. The gross margin is influenced by the crop, the manure amount, the fertilization options, the soil quality, previous crop effects, varying levels of liquid, crop incompatibilities, and other values, along with the respective monthly labor requirements. Other farm-wide constraints, like ecological focus area factors, are also considered. The resulting system is then optimized to target net profit and legislation compliance cf. optimization target in Table 2.

Fendji et al. [23] follows a similar approach, but the constraints and optimization targets are more explicitly defined. The constraints are (1) two crops cannot be planted in the same plot, (2) succession of crops from the same botanical family on the same plot is not allowed, (3) two crops of the same botanical family should not be planted at the same time on two adjacent plots (4) budgetary constraints (5) equipment and available labor (6) minimum nutrient requirements per crop and (7) estimated demand for each crop. The optimization target is the net profit, which will be analyzed in Section Optimization target. For maximizing the revenue, the resulting system uses a MILP solver.

MORDMAgro [21] follows a different approach: It pays more attention to uncertainty about the future. To model this, multiple possible future scenarios are estimated, consisting of two sets of variables. First, the historical weather data is divided into periods and transformed into discrete categories, namely: very low, low, medium, high, and very high with the addition of extreme weather events, the so-called El Niño and La Niña events. Secondly, the agricultural commodity prices are estimated based on historical data. In the second step, six cropping alternatives are defined. They consist of a crop and associated agronomic management, including cultivar/hybrid, planting date, planting density, row spacing, and fertilization level. The expected yield per combination is estimated using DSSAT. Thirdly, six metrics are defined to evaluate the different combinations of cropping alternatives and possible future scenarios. The three metrics are aggregations of (1) the utility, which is the total satisfaction experienced by farmers from the monetary value, the farm-wide-net-margin, and (2) the Return on Investment (ROI). The ROI measures the return on a particular investment relative to its costs. The first two aggregations are the expected value of (1) and (2), that is, the expected utility and the expected ROI. The second two metrics are the expected shortfalls. They measure the risk of an investment. Again they have been defined for (1) and (2) as estimated utility and estimated ROI. The third two metrics are the regrets. These are defined as the difference between a strategy's performance and the optimal performance. More specifically, the third quartile for the distribution of regret values for a given scenario for utility and ROI is used. As illustrated within the block simulation in Fig. 4b, the fixed costs are used as a seventh metric. As the last step, all metrics are calculated for all possible combinations of cropping alternatives and future scenarios. The farmer can then select the cropping alternatives with regards to her/his personal preferences, balancing the

Table 2
Attribute based comparisons of CRM tools on optimization target, farm type and location, resolution, output data as well as accessibility and adaptability.

CRM Tool	Optimization Target	Farm Type	Region	Resolution	Output Data	Accessibility	Adaptability
FruchtFolge [18]	• net profit • legislation compliance	• arable farms	• North Rhine Westphalia	• not stated	• crop plan and spatial allocation of different crops • fertilization plan • expected revenue • required workload • legislation compliance	• free of charge • open source • easily accessible (for German farmers)	• partly adaptable • modular design
FARMs [19]	• improve usability of DSSAT	• arable farms	• USA	• $10km^2$	• two scenarios in one field • one scenario in two fields	• free of charge • easily accessible	• adaptable
LAMPs [20]	• similarity to generic crop sequences	• arable farms	• USA	• $30m^2$ (resampled)	• observed crop sequences • proposed crop sequences • linked crop management operations	• free of charge • easily accessible	• not adaptable
MORDMAgro [21]	• net profit • robustness	• arable farms	• Argentina	• not stated	• set of robust scenarios • critical factors	• free of charge • open source • basic programming skills required	• partly adaptable • experts required
Peltonen-Sainio et al. [22]	• crop diversification	• non-organic, arable farms	• southern Finland	• not stated	• five year crop rotation plan	• free of charge • easily accessible (for Finish farmers)	• theoretically adaptable
Fendji et al. [23]	• net profit	• organic arable farms	• central Africa	• not stated	• crop rotation plan • expected revenue	• tool not available	• theoretically adaptable
von Lücken et al. [24]	• net profit • investment costs • risk of investment • positive nutrient balance • min. cultivation of same crops contiguously • min. months with same family crops on neighboring fields • min. months with fallow land	• arable farms	• Paraguay	• not stated	• crop rotation plan	• tool not available	• theoretically adaptable

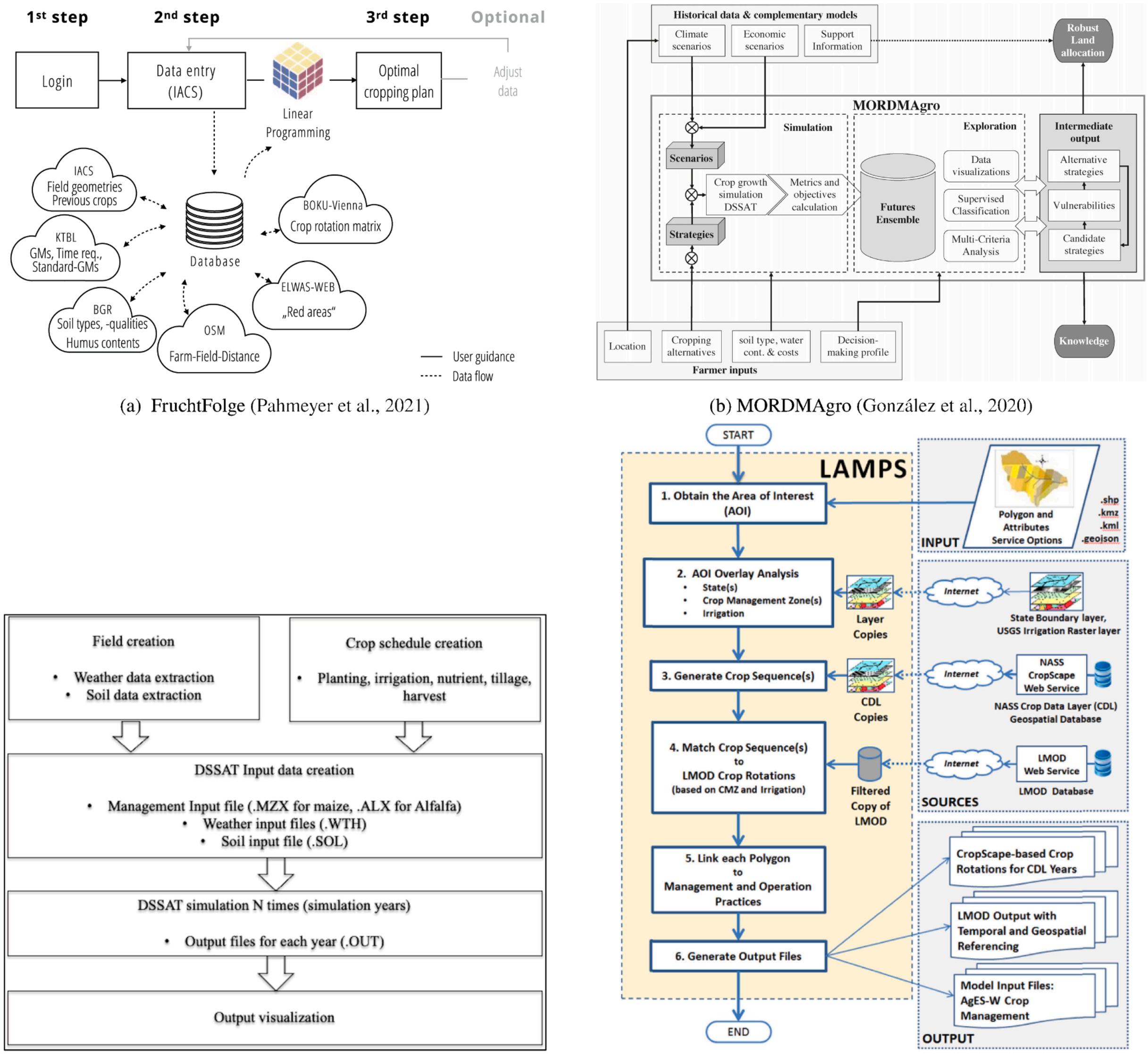
different metrics, cf. block intermediate output in Fig. 4b.

Peltonen-Sainio et al. [22] uses a scoring system to calculate a ranking for different crop choices. The system consists of three metrics. The first is the crop suitability per field. It is calculated from the field characteristics such as field size, field shape, field slope, distance to the farm center, proximity to a waterway, soil type, ownership, and currently used crops on these fields, using multinomial logistic regression, resulting in a crop suitability score. Next to the crop suitability score, the second metric is the crop rotation score. It uses the cultivation choices of the four previous years, with higher scores for more diverse cropping choices. The highest score, e.g., is given if three years of cereals and two years of break-crops were planted, and the lowest score, e.g., if the same cereal was planted all four previous years and suggested for the following year. The third metric consists of additional limitations like planting and harvesting dates of specific crops so that winter cereals cannot follow faba beans, and specific unfavorable cropping choices. Given the specific characteristics of a farm, this scoring system is used to produce a 5-year cropping plan.

LAMPs [20] produces crop rotation and management information by matching crop sequences from the land management and operations database (LMOD) [25]. LMOD provides already in use, available, generic crop rotation information. For a given field, all field characteristics are loaded from the USGS database, cf. step 2 in Fig. 4d. Then, the past crop sequence which was in use is estimated on the basis of historical data from the CropScape database, by calculating a confidence index for each possible crop for each year. The crops with the highest confidence indexes are selected and form a crop sequence. After that, the obtained crop sequence is matched with crop rotations from the LMOD database. An adjusted average confidence index is calculated for each combination, using a similarity measure with a weighting term to favor longer sequences. If a match is found, all available crop management information is loaded from LMOD and adjusted to the given information about the field. This process is repeated not only for the best matching confidence indexes but also for subsequent indexes.

FARMs [19] does not produce a cropping plan directly but facilitates the use of DSSAT so that the target group farmers can use DSSAT. It first loads data from the sources described in Section Input Data, using different software frameworks like Django, PostreSQL, and PostGIS. Thereafter, a GUI is provided, where the possible inputs are reduced in complexity, compared to the original DSSAT. All data is then combined as input to DSSAT, cf. process step *DSSAT input data creation* and *DSSAT simulation N times* in Fig. 4c. In the last step, the output of the DSSAT simulation over N simulation years is visualized by the GUI.

The CRM tool by von Lücken et al. [24] first defines a system of optimization targets and constraints. As optimization targets a wide variety, from the net profit via investment risk to positive nutrient balance can be set in this tool; cf. Section 6.2.1. The constraints are the crops sowing and harvesting dates. Evolutionary algorithms, in general, are computing a set of solutions from an initial population by combining the current population and its off-springs, created by genetic operators like mutations and crossovers. All evolutionary algorithms are randomly initialized. On the basis of this kind of algorithm, crop rotation plans are computed. The evolutionary algorithms used within this CRM tool are the (1) Strength Pareto Evolutionary Algorithm 2 (SPEA2), which utilizes a ranking based on counting the number of solutions the considered solution dominates, and a distance measure to the kth nearest neighbor. The (2) Non-dominated Sorting Genetic Algorithm 2 (NSGA2) uses an elitist procedure. The use of SPEA2 or NSGA2 are selected frontwise based on the crowding distance. A binary tournament mating selection is used to increase the selection pressure further. The (3) Reference Vector



(a) FruchtFolge (Pahmeyer et al., 2021)

(b) MORDMAgro (González et al., 2020)

(c) FARMs (Kim and Kisekka, 2021)

(d) LAMPs (Kipka et al., 2016a)

Fig. 4. Workflows and data schemata of four CRM tools.

Guided Evolutionary Algorithm (RVEA) and the (4) Non-dominated Sorting Genetic Algorithm 3 (NSGA3) are based on the procedure of NSGA2. They mainly differ in selecting the population elements of the next generation. RVEA uses a reference vector guided selection, based on each solution's convergence and diversity properties. NSGA3 utilizes a reference set to associate the elements of the population their closest reference point. Lastly, (5) MOEA/D decomposes the original problem into several subproblems, which are then optimized by performing evolutionary operations among their neighboring subproblems. The subproblems weight vectors define the neighborhood. In the final step, experts verified the realisticness of the resulting solutions, which are then evaluated using the inverted generational distance.

5.1.2. Input data

For providing a CRM tool for every farmer around the globe, intense foci must be set on the adaptability of CRM tools to different data sources and their usability. Thus, this section covers manual data import by the user and automated data import from available data sources.

5.1.3. User input data

The amount and type of data required, which has to be inserted by the user, varies considerably in all reviewed CRM tools. The interaction ranges from no mandatory inputs to quite long and specific definitions of each field. The tools with no mandatory user inputs allow for optional user inputs to improve and adapt the predictions to individual needs.

The tool by Peltonen-Sainio et al. [22] relies heavily on gathered expert knowledge so that usually, the farmers only provide their identification from the Natural Resources Institute Finland to set up the CRM tool. In case adjustments are needed, the farmers can finetune some parameters.

Similar to the tool by Peltonen-Sainio et al. [22], FruchtFolge [18] uses a user-centered design, requiring the user to have as minimal an effort as possible. Here, the minimal user input for the CRM tool to be able to work is the ZIB-code 4 a. The EU uses the ZIB code to individually identify every farm that has applied for EU-subventions and is comparable to the identification from the Natural Resources Institute Finland. The tool FruchtFolge uses this ZIB-code to import all other data points needed automatically. The user can adjust every data point of the automatically imported data to improve the system's performance and change its parameters to the individual needs.

LAMPs [20] requires little user input. Only the area of interests, i.e., the field locations and boundaries, have to be defined by the user, cf.

step 1 in Fig. 4d.

More user inputs are required for MORDMAgro [21]. Here, the user must insert the fields' locations with soil parameters such as soil type and water content. Additionally, the user must choose cropping alternatives.

For the tool developed by Fendji et al. [23], extensive user input is required. The user has to define which crops to consider, their botanical family, the available budget, the length of the time window for which the tools should produce a cropping plan and the number and size of the available fields.

The CRM tool by von Lücken et al. [24] strongly depends on user input as well. The user has to provide the field geometries and the soil's nutrient content. The crops have to be provided as well. The absorption and extraction of nutrients and the associated fixed costs must be entered by providing the crops, their name, and botanical family, together with the sowing and harvesting dates.

FARMs [19] also heavily relies on user input. Again, the user has to define the field locations, the planting date and crop choices, irrigation dates and methods, fertilizer use, and the tillage types, cf. input block crop schedule creation in Fig. 4c. Some exemplary inputs for the crops maize (Zea mays) and alfalfa (Medicago sativa) can be chosen from a list of possibilities; other crops must be added manually.

5.1.4. Automatic data import and data sources

Data provided by the user can be biased, and, e.g., some data like the type and quality of the soil are hard to obtain without measuring devices or sensors. These devices or sensors are usually very costly. Thus, it might be unfeasible for small-scale and subsidiary farmers to provide all needed data to CRM tools. Consequently, automatic data import from several data sources might deal with this problem. Because in theory, more and better data that can be accessed and used by the CRM tool leads to better crop rotation tables and planting suggestions.

The tool by Peltonen-Sainio et al. [22] primary data source is the Natural Resources Institute Finland named Luke. Luke is used for importing all needed field characteristics, such as the field size, the field shape, the field slope, the distance to the farm center, the proximity to a waterway, the soil type, and ownership, i.e., owned or leased fields. Every registered Finish farmer can access the Luke data source. The second data source used is the data source by Peltonen-Sainio et al. [26]. This data source evaluates the suitability of different crops for a given field parcel.

Besides the user input, the CRM tool by Fendji et al. [23] relays on historical data about the production of fruits and vegetables [27] in Cameron, and their prices [28].

The tool by von Lücken et al. [24] uses data sources similar to the tool by Fendji et al. [23]. Here, historical data about the production and prices of crops are imported. Within the paper, the origin of the data is not specified, but the data tables can be changed according to the user's preferences.

FARMs [19] imports weather data from the NASA POWER database [29] and soil data from the global high-resolution soil profile database for crop modeling applications [30]. Both databases are freely accessible and cover the whole globe, enabling the use of FARMs worldwide.

For MORDMAgro [21], historical weather data is imported from the Servicio Meteorológico Nacional [31]. In addition, historical crop prices are used, this time obtained from the Asociación Argentina de Consorcios Regionales de Experimentación Agrícola [32]. Six handcrafted cropping alternatives with associated fix costs are embedded that are considered in MORDMAgro. The data sources used by experts for generating the cropping alternatives are not mentioned in the paper by González et al. [21].

LAMPs [20] makes use of three data sources. The first source is the CropScape database by the US National Agricultural Statistics Service [33]. It contains information about current and historical land use and the cultivated crop types in the US. Secondly, the LMOD [25] provides generic information about crop rotations and their respective agricultural management operations, including dates of planting and harvesting, tillage depths, and intensity. This information is grouped in so-called conservation management zones, which vary in agricultural conditions such as soil type, quality, and agricultural use. Thirdly, a map about irrigation in the US is obtained from the US Geological Survey [34]. All data sources are accessible and freely available for areas within the US.

FruchtFolge [18] is tailored for the use within Germany. Therefore, various local, high-quality data sources are used. In the first step, the user logs in using the ZIB code. In the second step, based on the ZIB code, the Integrated Administration and Control System (IACS) database is accessed. The IACS database provides field geometries and historically cultivated crops for all fields. As second data source is the Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) [35], engl. board of trustees for technology and construction in agriculture, which provides open data access to farm planning data, such as rationalized historical yields, prices, and direct costs, like fertilizer and seeds, and costs and times for field working operations. Data about the soil quality is imported from the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) [36], engl. Federal Institute for Geosciences and Natural Resources. This data source provides soil types, soil quality, and humus contents. Another map is imported from the elektronisches wasserwirtschaftliches Verbundsystem für die Wasserwirtschaftsverwaltung (ELAS-WEB), engl. electronic water management network system for water management [37]. This map marks areas where fertilization restriction is in use. Lastly, CropRota, a value point matrix for different previous and subsequent crop combinations, developed by Schönhart et al. [38], is used. Except for the IACS database, all data sources are accessible and freely available. The IACS database is only accessible for registered farms.

5.1.5. Platform and accessibility

The platform on which the CRM tools run is an important indicator of whether the CRM can be run as standalone software or if a server infrastructure is needed.

5.1.6. Tools as a Web-Service

The following tools are all accessible as a web service. Thus, only an Internet connection and a standard web browser are required for using them. The CRM tool by Peltonen-Sainio et al. [22] will be realized by including it in the Luke's Economy Doctor portal as a web service, making it accessible and usable for free by every registered Finnish farmer. In Finland, this portal is well known among farmers, enabling its easy use. FARMs [19] runs as a web-service, too, and farmers can register themselves. LAMPs [20] is implemented as a web service as well and can be run on the cloud platform of the Colorado State University. Nevertheless, programming skills and knowledge about the web browser based tool jupyter notebook is necessary to instantiate LAMPs for every individual farm. FruchtFolge [18] can be accessed for free by every farmer, who has a ZIB code, as a web service. Further, if one likes to run an own instance, the source code is open-source. Nevertheless, the underlying algorithm of FruchtFolge is written in the fee-based programming language GAMS.

5.1.7. Other Platforms

The following CRM tools run on different platforms, are not accessible or have not been implemented. MORDMAgro [21] is written in the programming language R. Thus, an R environment is required to run the script. The MORDMAgro script is open source and freely available. For running the tool, basic programming skills are needed. Although the tool by von Lücken et al. [24] mentions the use of a database (PostgreSQL), no implementation or the source code of the tool itself is published yet. The CRM tool by Fendji et al. [23] was tested with different scenarios and implemented in the programming language Julia, but the implementation of the tool is not yet been released.

5.2. Usability and user experience

The usability and user experience of the seven selected CRM tools should be initially tested by user studies. Nevertheless, due to underlying data sources and the non-existent of two tools, unbiased user studies with farmers on the same virtual fields were not feasible. However, Fig. 5 illustrated the GUIs of FARMs, FruchtFolge, and LAMPs. By comparing LAMPs with FARMs and FruchtFolge, it can be seen that the user interface of LAMPs is not created focusing on the user center design process. LAMPs execution script is still clearly structured so that with basic programming skills, farmers might run it in an Python environment.

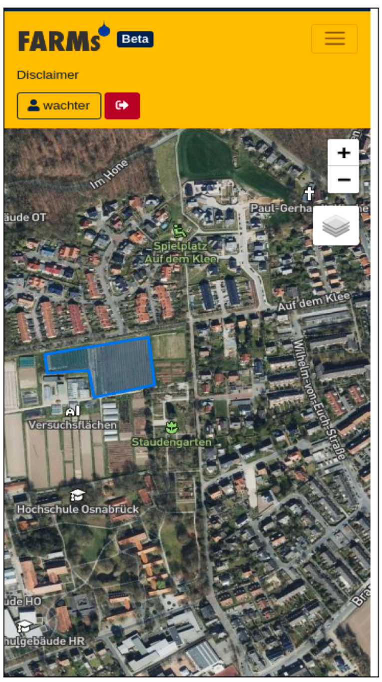
6. Comparison of crop management tools

Focusing on the target group farmers, the attributes and properties for the comparison are defined before, each tool is detailed compared. Tables 1 and 2 summarizes the outcome.

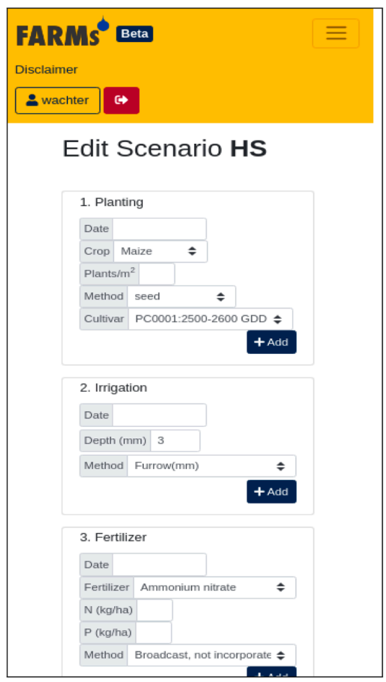
6.1. Used comparison attributes

To objectively compare the CRM tools, different attributes are selected. The selection was made having in mind that for reaching the SGD-2, the most important target group are small-scale arable farmers outside of Europe and the US. Next to the basic elements of CRM tools, cf. Section 5.1, six attributes are selected.

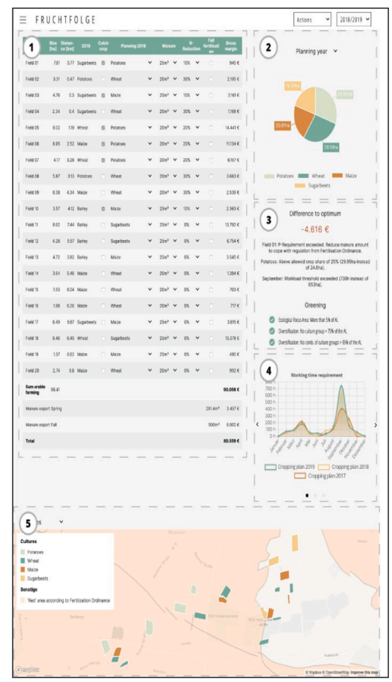
As the first attribute, the optimization target of the CRM tools is selected. As mentioned before, some tools have single, while others have



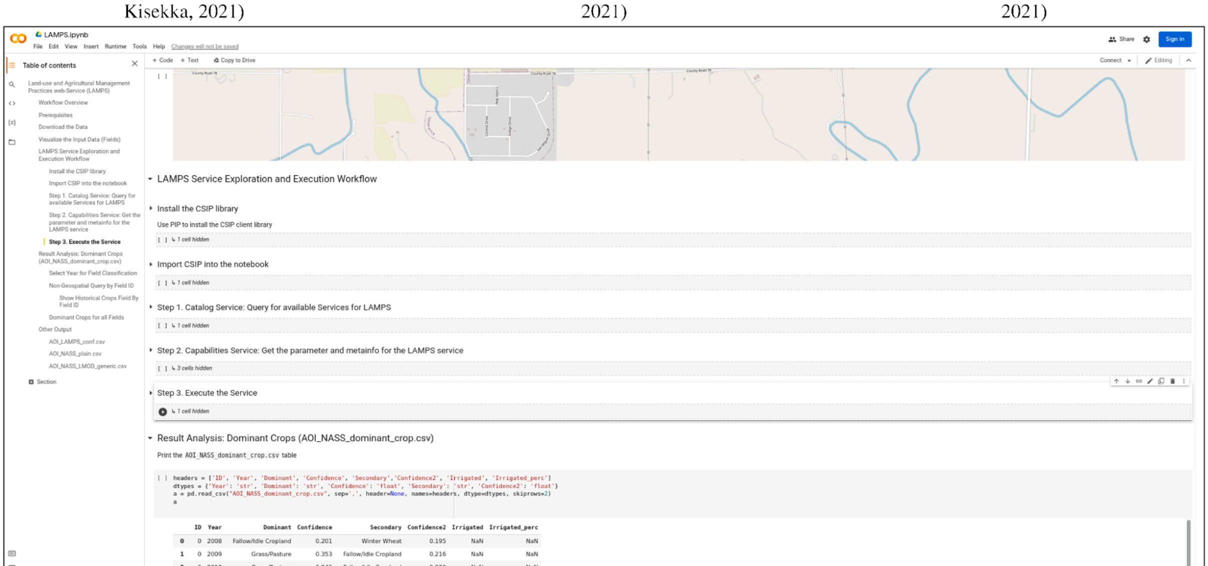
(a) FARMs - field selection (Kim and Kisekka, 2021)



(b) FARMs - data input (Kim and Kisekka, 2021)



(c) FruchtFolge - output (Pahmeyer et al., 2021)



(d) LAMPs (Kipka et al., 2016b)

Fig. 5. GUIs of three CRM tools; (a) to (c) CRM tools as web service and (d) as R script.

multi-objective optimization. Since optimizing crop rotations to match an objective or several objectives, the attribute optimization target is essential.

The second attribute is the target group, as discussed in Section 3, and its associated farming type. The farming type describes what is produced at the farm, i.e., crops–arable farms and animal products—pastoral farms, organic or non-organic farming, etc.

The third attribute is the region for which the CRM tool is designed. According to Fig. 1, hunger is predominantly a problem in Africa and Asia. Thus, it is essential to consider the regional specifics of these regions, especially the availability of high-quality data sources.

The fourth attribute is the spatial resolution. It determines the size of the fields the CRM tool can be used for. The smaller the fields, the more important is a high spatial resolution.

The fifth attribute is the model's output data. Some tools have a single output, while others have multiple, depending on their optimization target and configuration. The output format is also important to judge its user-friendliness. Thus, the accessibility of the tool, i.e., how easy a user can gain access to it, is included as well.

The sixth attribute is the tool's adaptability. Whether a tool can be used in different regions, different farm sizes, farm types, and different crops decide how flexible a tool is. The better a tool can be adapted to different circumstances, the broader its possible range of application.

6.2. Comparison

The following paragraphs compare and discuss the defined attributes of the CRM tools, which are summarized in Table 2.

6.2.1. Optimization target

The optimization target can be one or several objectives the CRM tools try to maximize or minimize. Generally, for most tools presented here, this is the net income. As a single-objective tool, the tool by Fendji et al. [23] uses the maximization of the net income as the only optimization target. LAMPs [20] objective is to maximize the similarity between crop sequences that are already in use and theoretical optimal crop rotations. The last single-objective CRM tool is the tool by Peltonen-Sainio et al. [22], which maximizes the diversity of crops in the proposed crop rotation. MORDMAgro [21] and FruchtFolge [18] can either be deployed as single-objective tools, optimizing on the net-income, or as multi-objective tools. In the multi-objective case, MORDMAgro proposes a set of rotations with different degrees of certainty or risk. The different degrees of certainty enable the user to select a suboptimal crop rotation concerning the maximal net income, but with a higher degree of robustness and less risk. FruchtFolge's multi-objective setting considers the use of fertilization to comply with German legal restrictions on the use of fertilization. FARMs Kim and Kisekka [19] has a single objective in the sense that it facilitates the use of the crop simulation model DSSAT. It is multi-objective in the sense that DSSAT can be used for various optimization targets. The CRM tool by von Lücken et al. [24] is a multi-objective tool. It optimizes seven targets: (1) maximization of the net profit, (2) minimization of the investment cost, (3) minimization of the risk of investment, (4) maximization of the positive nutrient balance, (5) minimization of contiguous crops of the same family minimization of months where crops from the same family are on neighboring fields and (7) minimization of the months where a field is fallow.

6.2.2. Farming type & target group

Some CRM tools try to facilitate the decision-making of crop rotation only for arable farmers, as opposed to tools that consider pastoral farming as well. The tool by Fendji et al. [23] is restricted to organic arable farms. MORDMAgro [21], FARMs [19], LAMPs [20] and the tool by von Lücken et al. [24] are used for arable farming. FruchtFolge [18] includes minor options to consider pastoral farming, but only in regards to manure availability. Peltonen-Sainio et al. [22] restricted their tool to non-organic farms and uses different parameters if a farm includes pastoral farming, e.g., the area of required grassland. Since CRM tools for non-farmers are excluded beforehand, all tools target farmers.

6.2.3. Region

Most of the existing tools target farms in Europe and the US, as illustrated in Fig. 6. FruchtFolge [18] and Peltonen-Sainio et al. [22] are tailored for Germany and Finnland, respectively. LAMPSs [20] is only applicable in the US. Outside of Europe and the US, MORDMAgro [21] uses data from Argentina, the CRM tool by Fendji et al. [23] uses data from Cameroon and von Lücken et al. [24] is tested with data from Paraguay, but the three do generally not restrict their use to the respective regions. Only FARMs [19] can theoretically be used worldwide, although adjustments are only possible for farms in the US.

6.2.4. Spatial resolution

The spatial resolution determines the minimal field size for which a CRM tool can be used. A high spatial resolution is necessary for small-scale farms with relatively small fields. Only two tools explicitly define the spatial resolution, namely LAMPs [20] and FARMs [19]. The global high-resolution soil profile database for crop modeling applications [30] used by FARMs has a resolution of 10km. Thus, FARMs spatial resolution is $10km^2$, but can be increased if the user provides a higher resolution input. LAMPs resolution is $30m^2$. The USGS database has a resolution of $250m^2$, but gets resampled to $30m^2$. All other tools do not define the spatial resolution explicitly. FruchtFolge [18] highlights the importance of a high spatial resolution. It's spatial depiction of the fields allows them to be arbitrarily small. In the description of the tool by von Lücken et al. [24], the field size is mentioned, but it is not further specified. MORDMAgro [21] and the tool by Fendji et al. [23] do not use field sizes at all. The former only uses the fields locations in terms of the coordinates, and the latter only considers the fields' adjacency.

6.2.5. Output and accessibility

The term accessibility is used to describe how the tool can be obtained and used. This term includes the platform the CRM tool runs on. The output makes the result of the computation accessible to the user. The output format determines how easy the farmer might understand and interpret the crop rotation plan. The tool by Peltonen-Sainio et al. [22] outputs a crop rotation plan for every field parcel. The exact format of the output is not described further; the same holds for the CRM tool by von Lücken et al. [24]. The output of Fendji et al. [23] are two simple plots: The first plot is a grid with the individual field parcels on the x-axis and the time on the y-axis. The boxes are filled with the crop to be planted. The second plot is a line chart with the available resources on the x-axis and the predicted income on the y-axis. This output format is straightforward to understand and use. FARMs [19] visualizes the output as a map on the website of the web service, and visualizations from DSSAT are used as well. The exact output format is not clearly described in the companion paper, and because the web service is still in the beta version, no further description can be given. The output of LAMPs [20] consists of three parts: (1) contains the dominant crops for the field, (2) contains the generic crop rotations and linked management options, and (3) is an input file for another model, the component-based AgroEcoSystem-Watershed (Ages-W) model [39]. All three outputs can be downloaded as.csv files. The output of FruchtFolge [18], cf. Fig. 5 (Fig. 5c), consists of five parts: (1) a table showing the crop recommendation for each field, (2) a pie chart with crop shares at farm level, (3) a box that shows compliance with German legal restrictions and their influence on the farms' profit, (4) a line chart showing the monthly workload and the predicted profits, and (5) a map showing the spatial allocation of the crops. All outputs are easy to understand and interpret.

6.2.6. Adaptability

Worldwide agriculture differs highly, as the world is unique in every

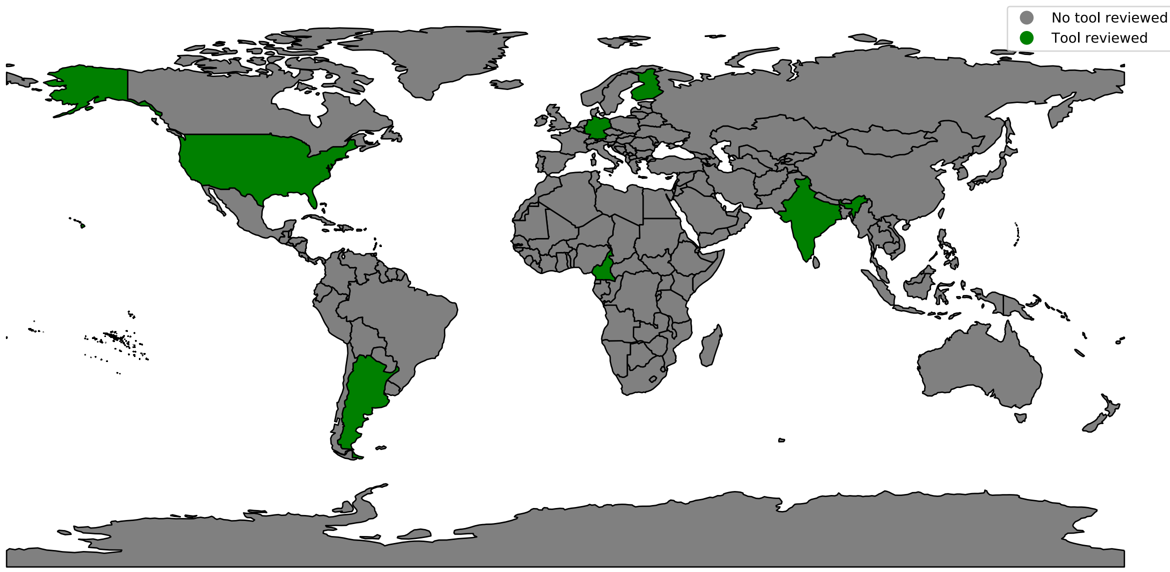


Fig. 6. Countries where the compared CRM tools are initially designed for.

region, so it is local agriculture. Multiple factors have to be taken into consideration, from biological essentials to socioeconomic circumstances. Thus, for the tool to be applicable globally, its adaptability to different situations is crucial. Therefore, the CRM tools are divided into four categories: *Not adaptable* are tools where it is not possible to change the input pipeline to make the tool applicable in other regions. *Theoretically adaptable* tools that are not open source. These tools provide the underlying algorithm with a formal definition but do not provide the implementation. These tools are called theoretically adaptable, because it is possible to implement them, but it would have to be done from scratch. *Partly adaptable* tools in this category can be modified in the sense that the underlying algorithm does work on other data sources. The challenge here is finding adequate data that can replace the original data from the original application location. Lastly, *adaptable* tools that can be used in any region of the world, without further modification.

Not adaptable is LAMPs [19]. LAMPs combines three databases from the US to facilitate the use of DSSAT. For farmers outside of the US, these databases can not be used. The whole tool is designed and implemented to combine these three databases and facilitate their use. Thus, replacing them would mean to re-implement the whole tool. It can only be used in the US. Theoretically adaptable are the tools by Peltonen-Sainio et al. [22], von Lücken et al. [24] and Fendji et al. [23]. Here, the underlying algorithms are described in detail, and the data sources are exchangeable, but the source code of the tools is not available on the Internet. The tool by Fendji et al. [23] relies heavily on user input. It does not matter where the user

and the fields are. Thus, the required inputs and the underlying algorithm do not depend on the region the tool was initially designed for. On the other hand, the automatically imported data is from central Africa. To adapt the tool to a different region, comparable data for this region must be provided. The CRM tool by von Lücken et al. [24] relies heavily on user data as well. Similar to Fendji et al. [23] tools, the underlying algorithm is not designed for a specific region, but tested with data from Paraguay. Given the correct data, the tool could also be deployed in other regions. Peltonen-Sainio et al. [22] CRM tool, automatically imported data is exclusively finished. Adapting the tool to other regions, all data sources needed to be replaced.

Partly adaptable tools are MORDMAgro [21] and FruchtFolge [18]. These two tools are open source and can be adapted to other regions, if the input data sources are exchanged accordingly. MORDMAgro [21] makes use of two data sources, which would have to be exchanged. The third data source used are the six cropping alternatives. They were designed by experts on farming in the test region. For other regions, cropping alternatives would have to be defined by experts for the respective regions. FruchtFolge [18] is strongly modular. It uses six different data sources, which mainly cover Germany. Although the focus is strongly on one country, it is a promising tool for other regions because of its modular design. FARMs is adaptable [20]. It is by design applicable worldwide, because the input data used here is available globally.

7. Results – Crop management tools for every farmer

CRM tools for every farmer worldwide? By considering a CRM tool that can be used by farmers worldwide, it has to fulfill the requirements as defined in Section 3 and 5. These requirements can be summarized as (I) does it run on a smartphone? (II) does it work for small fields? (III) does it provide worldwide coverage? (IV) does it work with limited network coverage? (V) is it free of charge? (VI) does it propose an appropriate solution to the crop planning problem?

Based on the comparisons of the basic elements, cf. Table 1 and the attribute-based comparisons in Table 2, the above mentioned requirements are evaluated. All of the five available CRM tools do not support at least one requirement, as can be seen in Table 3. Due to their adaptability, FruchtFolge [18] and FARMs [19] are promising starting points for a CRM tool supporting farmers worldwide.

8. Discussion

For small and subsidiary farms outside of Europe and the US, CRM tools could greatly help the crop planning problem and contribute to reaching SGD-2. Most CRM tools reviewed are implemented as web services. Unlike traditional desktop applications that rely on hardware with high computational power and additional software frameworks, they are platform-independent and outsource the computational costs to servers. The minimal hardware to run such an application can be a smartphone with an Internet connection. The rapid spread of smartphones worldwide enables farmers without extensive computer hardware to access and use well-designed web services. Well-designed web services have the distinctive feature that provides most of their functionality even without an Internet connection. For CRM tools, e.g., the crop rotation plan and the manual data input can be realized as an offline feature, and only the calculation of the crop rotation plan is done online. However, only one benchmarked tool has worldwide data

Table 3
Comparison of available CRM tools with focus on the worldwide use by every farmer.● indicate full, ◐ indicate partially or not specified, and ○ indicate no support.

	run on smartphones	small fields	worldwide	limited network coverage	without payment	appropriate function
FruchtFolge [18]	◐	●	○	◐	●	●
FARMs [19]	●	○	●	◐	●	◐
LAMPs [20]	◐	●	○	◐	●	◐
MORDMAgro [21]	○	◐	○	○	●	●
Peltonen-Sainio et al. [22]	●	◐	○	◐	●	◐

coverage, while the others are designed for a specific region. The regional specialization depends on the data sources available. These data sources improve the tool's user-friendliness by reducing the manual user input. However, on the other hand, applicable regional data sources must be found to employ the tools in different regions of the world. Building a tool with worldwide coverage requires either worldwide high-quality data sources or a mechanism for the user to provide the required data easily by, e.g., simple interaction. A combination of both is possible as well.

Next to the data from data sources and by manual input, the underlying algorithm must cope with different field sizes, in the majority of cases small field sizes. By focusing on low-income countries, 60% of the farms work with small field sizes below one hectare, cf. Fig. 2(c). Thus, a CRM tool for every farmer needs to consider these small fields as spatial resolution. However, the minimal spatial resolution of a tool critically depends on the spatial resolution of the input data, highlighting the need for high-quality data sources and simple interaction methods for manual data input.

The appropriate function of CRM tools for tackling the SDG-2 is to generate easy-to-understand and practicable crop rotation plans, which maximize the farmers' yield and income in a sustainable way. The tools reviewed here differ in their appropriateness. Adjustable objectives, taking into account the individual farmers' needs and preferences, are inevitable to generate a useful crop rotation and increase the acceptance of the tool. Many fee-based CRM tools are available, but the costs imposed to deploy these tools are beyond the possibilities of most small-scale farms in low-income countries. Because of the limited available resources of farmers in low-income countries, a CRM tool for every farmer's worldwide use must be free of charge, provide sustainable crop rotation plans with yield and income as optimization targets, and support automatic as well manual data input.

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