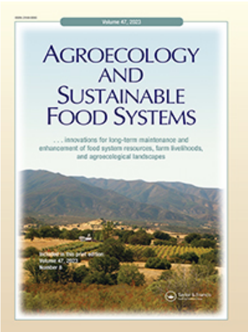

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Combination of observational and functional trait-based approaches in developing a polyculture design tool

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ABSTRACT

Models of species composition in diversified cropping systems utilize mostly functional trait-based or observation-based approaches. We argue that a combination of these two approaches makes polyculture design tools more robust. We assessed quantity, quality, and complementarity of information from multiple sources for designing diversified cropping systems with vegetables and spice crops for cold temperate climate. Trait and observational data were integrated from: (i) two grower-oriented and one academic crop database, (ii) a survey of farmers practicing community-supported agriculture, and (iii) a systematic literature review on the use of spice crops in vegetable farming. Survey results reveal that the farmers were capable of achieving medium to good levels of their main goals, but failed to reach desired multifunctionality with their polycultures, which can be potentially improved with computational tools. None of the analyzed data sources provided a comprehensive dataset for all target crops and functional traits. However, source combination allowed for design from known crop companions (farmers survey and grower-oriented databases), to addressing specific pest problems (literature review), and increasing functional complementarity and facilitation by trait matching (academic and grower-oriented trait databases). Integrating information from different sources increased the number of crop combination options but also planning and management complexity.

KEYWORDS
Sustainable agriculture; intercropping; modeling; vegetables; spice and aromatic plants

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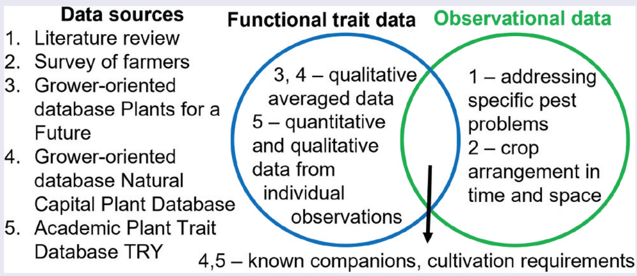

Combination of functional trait-based and observation-based approaches within a polyculture design tool.

Introduction

Agricultural systems cover approximately 40% of the land surface of the Earth and thus have a significant biospheric impact (Webb et al. 2020). This impact is likely to increase as the population grows by an additional 1.5–3 billion by 2050 and requires 35% to 56% more food production globally than was produced in 2010 (van Dijk et al. 2021). This raises questions about the way food is produced. Contemporary industrial agriculture has numerous drawbacks due to its low energy efficiency, dependence on availability of scarce and nonrenewable resources, and elimination of biodiversity (Webb et al. 2020). Therefore, progress toward a more low-risk ecologically functional agriculture is required (Altieri, Letourneau, and Davis 1983), one that will be compatible with ecosystem resilience to climate change and reduced resource input (Lescourret et al. 2015; Wezel et al. 2014). Many land-based options that deliver carbon sequestration in soil or vegetation, can be applied without competing for land and have the potential to provide multiple co-benefits (Arneth et al. 2019). Using polycultures – the simultaneous cultivation of several crops in the same space – is one way to diversify agricultural systems. Studies show that polycultures can be more productive (Smith et al. 2017) and have multiple environmental benefits such as erosion control and water quality regulation (Daryanto et al. 2018).

But, field performance of crop polycultures often depends on pedoclimatic and management factors, and multiple agronomic, socioeconomic, and environmental objectives need to be considered. Therefore, successful design of diversified cropping systems requires both improved conceptual and management knowledge and its exchange, which can be facilitated through participatory elements, ensuring place-based experience. Nowadays digital instruments for designing crop polycultures are being developed as decision support tools for farmers (Malézieux et al. 2009). Currently, such tools are grounded on mostly functional trait-based approaches or on observational data. Trait-based approaches allow species comparison and prediction of species interactions based on physiological, morphological, chemical or phenological characteristics, but they lack real-world verification (Damour et al. 2018; Martin, Isaac, and Manning 2015). Observational approaches document successful polycultures in the field collected from experts, including researchers, agricultural extension workers, and agroecology practitioners, but they lack understanding of underlying mechanisms and therefore limit prediction of success in new settings. A simple solution for balanced and comprehensive combination of both (trait-based and observation-based) approaches and the appropriate operationalization of this knowledge (tool) has not previously been tried.

This research **hypothesizes** that a triangulation (cross-validation) approach using modeling that integrates both crop trait and observational data is a methodologically feasible approach to increase the quantity and quality of data used in designing crop polycultures. To demonstrate this, we pooled information from five complementary and accessible sources, thus enabling several scientific and agronomic facets relevant for designing crop polycultures. Specifically, we accessed one academic and two grower-oriented databases (both containing trait data and the latter including information on known crop compatibility, cultivation requirements, and environmental tolerances). We also drew from a systematic review of the academic literature (indicating both potential and proven crop combinations, particularly for addressing specific pest problems) and from a survey of an expert group (providing the range of possible crop associations in space and time). We focused on promoting diversified farming at the plot scale, in particular for vegetable growers in cold temperate climates. Given wide use of spice and aromatic crops and their extracts in diversified vegetable farming, in particular for biological pest control (Gómez Jiménez and Poveda 2009; Raveau, Fontaine, and Lounès-Hadj Sahraoui 2020), a systematic literature review was performed to identify aromatic crops as reported or prospective companions in vegetable cultivation.

We selected German, Austrian, and Swiss farmers practicing Community-Supported Agriculture (CSA) as an expert group for this research since this farming practice is often linked with agroecological principles. CSA is also based on direct linkage between farmers and customers, where farmers directly respond to consumer demands by growing numerous species of fruits, vegetables, and aromatic herbs (Opitz et al. 2019). Therefore, these growers possess solid experience in diversified farming and also have a potentially high demand for knowledge transfer, given the large number of crops they are trying to manage simultaneously. German-speaking countries, with about 400 existing CSAs (Netzwerk Solidarische Landwirtschaft e.V., Kattge et al. 2020) including 131 pure vegetable and 107 mixed plant and animal production CSAs, provides a good opportunity to gain insights on practice, experiences, beneficial conditions, and limitations of diversified vegetable production systems.

The **aim** of this research is to evaluate the benefits of combining trait-based and observation-based approaches in developing polyculture design tools. We examined the extent to which the present crop diversification practices of CSA farmers meet their goals, and identified gaps that can be possibly bridged with digital tools. We also analyzed quantity, quality and complementarity of information from accessible sources. Finally, we discuss the utility of polyculture design tools depending on the scope of growers' challenges which these instruments are designed to address, and the robustness of solutions which these tools can generate.

Materials and methods

Farmers survey

Description of study area

As we did not aim to correlate crop diversification practices with pedoclimatic conditions, reporting farm location was optional for respondents (in accordance to the data minimization principle (General Data Protection Regulation 2016, art. 5(1)(c); Regulation (EU) 2018/1725 2018, art. 4(1)(c)). GPS coordinates were identified for reported locations. Soil types were retrieved from interactive national soil datasets for Germany (Lower Saxony Ministry for the Environment, Energy and Climate Protection n.d.), Austria (Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft n.d.), and Switzerland (Swiss federal authorities n.d.). Climate data were retrieved from an updated world map of the Köppen-Geiger climate classification (Peel, Finlayson, and McMahon 2007).

Data gathering

This study used semi-structured, open-ended surveys and interviews. All 269 German, Austrian, and Swiss vegetable farmers registered on the website of the German-speaking CSA association (Netzwerk Solidarische Landwirtschaft e.V 2020) were selected for this research. Growers were contacted by e-mail and offered either to participate in an online survey, in German or in English, or in an individual video interview in English conducted by the lead researcher. Twenty-three growers participated in the survey and two in the interview.

Both the survey and interview guide included questions about observed benefits and constraints of polyculture practices, goals and challenges, the usage of polyculture design tools, and desired polyculture schemes. Participants could optionally provide details of applied and planned polyculture strategies to meet their primary goals (important motivations) whenever they utilized popular crop combinations or when they developed any tailored solutions. In addition, farmers could report crop arrangements in time and space as well as provide recommendations for peer growers on establishing and managing reported crop combinations.

All Likert-scale questions were categorized into three broad topics: goals and results achieved, future directions and constraints, and crop arrangement in time and space. In turn, goals and results were further subdivided into the following categories: improving soil fertility, improving crop pollination and biocontrol, creating a beneficial physical environment for crops, improving farm economy and work performance, and agroecosystem services not linked to crop production. Respondents could also rate the overall impact of crop diversification. Constraints were categorized as following: poor performance of polycultures, management constraints, economic and regulatory constraints, and lack of access to knowledge and information. The number of responses was tallied for each category and subcategory.

Data analysis

Likert-scale responses were evaluated using Wilcoxon rank sum tests. Level of agreement with each statement was treated as a factor (5 = Very important, 4 = Important, 3 = Somewhat important, 2 = Not sure and 1 = Very unimportant). Volunteer responses were compared between the past and future goals (functions that growers had wanted to improve when they first designed the existing polycultures, or functions they would like to see further improved in the future).

Databases of crop traits

Data gathering

A list of the most popular cash crops by German-speaking CSA farmers was constructed based on a combined complete crop list from eight randomly picked farms that reported crop lists on their online profiles at the website of SOLAWI – German-speaking solidarity agriculture network of Europe (Netzwerk Solidarische Landwirtschaft e.V 2020). The constructed crop list included 38 fruit, root, tuber, and bulb vegetable crops and 38 leaf vegetable crops; 72% out of these 76 crops were produced on at least 3 farms. Crop trait information for these 76 crops was retrieved from two grower-oriented databases referred to as PFAF (Plants for A Future charity 2000) and NCP (Natural Capital Plant Database, Westmoreland and Halsey 2001) using custom web scraping algorithms. Data was also obtained from the TRY research database (Kattge et al. 2020) where public data were requested.

160 traits reported in the TRY database for 14 selected crops each representing a different family were identified by the primary author and agreed upon with coauthors based on expert opinion about their importance as potential predictors of agroecosystem services in crop polycultures. Traits

were grouped into the following categories: plant phenology, modulation of environmental conditions, plant architecture, nutrient cycling, water use efficiency, cultivation requirements, pest and disease resistance, weed control, intercropping capacities, attracting pollinators, weed potential, integration with livestock, and human usage. Each of these categories were further divided into relevant subcategories. 62 traits and crop functional characteristics from the PFAF database and 86 from the NCP database were also incorporated into respective categories.

The quality of the constructed trait database for each agroecosystem function and environmental tolerance was assessed by the number of species and number of observations (for TRY database) reported for individual traits. Traits reported for a minimum of three species were utilized in our polyculture design algorithm. The predictive capacity was assessed as a number of traits which can serve for direct and indirect prediction of particular functions.

Data analysis

For traits retrieved from the TRY database, where quantitative trait values were reported from multiple observations and studies, mean values were used in case of normal trait value distributions, and median values in case of trait value distribution other than normal. Value distributions were analyzed with Shapiro-Wilk Test using an online calculator (Statistics Kingdom 2017) using MS Excel script designed to feed data into this calculator and to retrieve outputs. Quantitative trait values were further divided into 3 bins defined as: Low (1 quartile), Medium (2 and 3 quartile), and High (4 quartile).

Systematic literature review

Given the wide use of spice and aromatic crops in diversified vegetable farming, in particular for biological pest control, a systematic literature review was performed to identify aromatic crops as reported or prospective companions in vegetable cultivation. A bibliographic search of peer-reviewed literature published to-date was conducted on 19 March 2021 from ScienceDirect Elsevier's platform because it provides an easy access to full-text content of journals, books, and reference works published by Elsevier and other publishers. Therefore, it is well suited for providing a proof of concept and constructing a dataset of published observations under conditions of limited researcher resources. The limit of this platform is that it returns the first 1000 articles ordered by relevance and does not offer comprehensive bibliometric analysis or evaluation features. We used a search query that combined synonyms for spice and aromatic plants either with synonyms for polyculture systems and key polyculture terms, or with synonyms for biological control. The search for sources pertaining to spice and aromatic plants was conducted as follows: ((spice OR aromatic OR culinary) AND (plant OR crop OR herb) OR "essential oil"). This search was combined with the polyculture search, as follows: (polyculture OR "cover crop" OR "green manure" OR "catch crop" OR "crop rotation" OR "crop sequence" OR "crop diversity" OR "allelopathy" OR "intercrop" OR "relay cropping" OR "double cropping" OR "alley cropping" OR "agroforestry" OR "strip cropping"). And the spice and aromatic plants search was combined with the search for biological control, as follows: ("biological control" OR biocontrol OR "biological pest control"). Subsequent article screening and analysis was performed by a single reviewer (primary author).

Search protocol was the following: ((spice OR aromatic OR culinary) AND (plant OR crop OR herb) OR "essential oil") AND ((polyculture OR "cover crop" OR "green manure" OR "catch crop" OR "crop rotation" OR "crop sequence" OR "crop diversity" OR "allelopathy" OR "intercrop" OR "relay cropping" OR "double cropping" OR "alley cropping" OR "agroforestry" OR "strip cropping") OR ("biological control" OR biocontrol OR "biological pest control"))

Titles and when necessary abstracts of 2335 original research and 582 review articles were screened and publications reporting exclusively tropical plants were excluded from further analysis. 181 potentially suitable records were retrieved, where publications reporting effect of spice or aromatic crops or their extracts exclusively on trees were excluded, and 63 publications reporting effect on vegetable crops were further analyzed.

Namely, the scope of each study was recorded (*in vitro* study, pot or greenhouse study, field trial with no repetitions, field trial with repetitions, field trial in various pedoclimatic conditions), as well as the mode of interaction (intercropping, crop rotation, mulch, extract, volatiles, soil amendment). Interactions were classified as positive, negative, and neutral and divided into the following categories: nutrient and soil organic matter provisioning and cycling, pest and disease control, weed suppression, growth suppression of intercropped plant, growth promotion of intercropped plants. The size of effect, measurement units, and prospective mechanisms were identified for each category whenever reported.

Keywords of selected articles were retrieved and the most common keywords in each synonymic chain were identified.

Dataset from the systematic literature review is deposited into the BonaRes Repository (Ardanov et al. 2023) and embedded into the polyculture design tool accessible by the following link:

https://docs.google.com/spreadsheets/d/1tVVakbeYTiDV2q9PDRvFZxul_nzpADw5CsriFCHRgFU/edit#gid=2027267386

Polyculture design tool

A beta version of the polyculture design tool was supplemented with narrative and video guidelines and produced on Google sheets platform, accessible by the following link: https://docs.google.com/spreadsheets/d/1JzS68FWbju8po9K-e-V5-6UsUjE3YXYdynLdrWyoMFs/edit?usp=sharing. The tool is hosted on our project webpage: http://visegrad.permakultura.sk/polycultures/. Version stability is provided by spreadsheets protection with designated ranges accessible for editing by tool users and integrated scripts to erase users' input by subsequent tool users. Initially, the algorithm operates with up to five user-specified vegetable cash crops available in our database and with selected companions retrieved from NCP and PFAF databases. Crops are grouped into one to five management "Zones" according to user-specified soil conditions, light availability, and tolerances to environmental stresses and pollutants, and later each polyculture is designed individually. In addition to companions reported in databases, the user can include spice and aromatic crops from our systematic literature review database These crops can be included as companions of selected crops, for biological control of defined pests or for attracting defined pest predators, and for control of defined weed species. Polycultures can also be complemented with crops reported as companions by survey participants where possible spatial and temporal arrangements are visualized as described by respondents. Finally, complementarity in polycultures can be increased stepwise by preferred order of importance in the following categories: plant architecture and growth cycle; nutrient cycling; pest, disease resistance and pollination; and companion cropping and integration with livestock.

Whenever the databases report different levels of particular trait values, the most frequent options are automatically selected. Alternatively, a user can report trait values of selected crops based on personal experience or from review of additional information sources. Each time when new crops are included into polycultures, known incompatible crops are identified and excluded. To compensate for database and algorithm limitations or potential errors, the user can intentionally include companions with potentially incompatible environmental requirements (site conditions) or keep crops with reported incompatibility in designed polycultures.

Results

Farmers survey results

Most respondents reside in regions with fertile (brown earth – 33%, cambisols – 33%, luvisols – 17%,) or moderately fertile (podzols – 17%) soils (Figure 1a). Climate conditions in this sample of respondents were variable: Cfb (temperate, without dry season, warm summer) – 50.00%, Dfb (cold, without dry season, warm summer) – 16.67%, Dfc (cold,

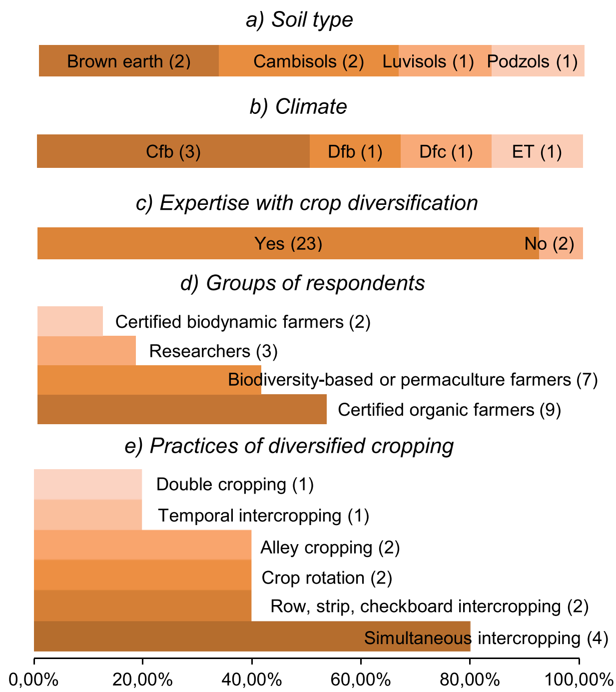

Figure 1. Profiles of surveyed farmers represented as column charts. *The numbers in parentheses indicate the number of responses received (n = 25). Data source: Survey of farmers.*

without dry season, cold summer) – 16.67%, ET (Polar, Tundra) – 16.67% (Figure 1b).

The majority of respondents, namely 23 participants out of 25, had previous experience with cultivating crop polycultures (Figure 1c). Participants identified themselves as “biodiversity-based or permaculture farmers” (41%), “certified organic farmers” (53%), “certified biodynamic farmers” 12%, “conventional farmers” (0%), “researchers” (18%), and “agriculture consultants or permaculture designers” (0%) – this grouping was not mutually exclusive (Figure 1d). Farmers utilized various crop integration practices: 80% – simultaneous intercropping; 40% – row, strip, and checkboard intercropping, 40% – crop rotation; 40% – alley cropping; 20% – temporal intercropping, and 20% – double cropping (Figure 1e).

The average plot size of respondents was 9.47 ha ±10.13 ha ranging from 2.00 to 21.00 ha (Figure 2a). On average, polyculture cropping systems occupied 36.64% of the total farm plot area and ranged from 2.22% to 100.00% (Figure 2b). Surveyed farmers managed diverse cropping systems with on average 21 ± 14 fruit, root, tuber, and bulb vegetable species, 35 ± 10 leaf vegetable species, 7 ± 4 cover crop species and 2 ± 1 livestock species (Figure 2c).

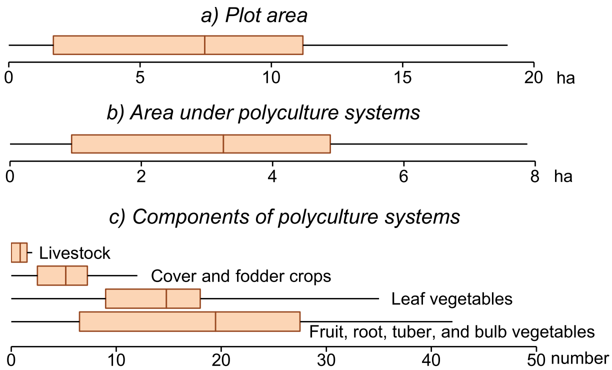

Figure 2. Profiling of surveyed farmers represented as boxplots. *Boxplots show minimum, 25-percentile, mean, 75-percentile and maximum values (n=25). Data source: Survey of farmers.*

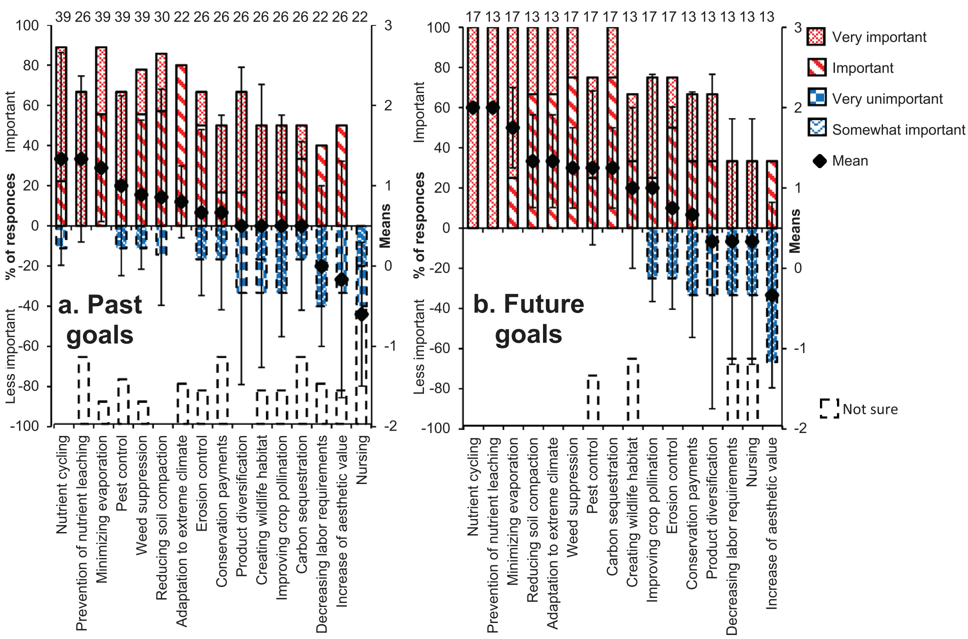

Figure 3. Growers' goals for crop polycultures. *Past goals (a) – functions that growers wanted to improve when they designed existing polycultures. Future goals (b) – functions that growers want to improve in existing polycultures or to achieve with transitioning to polycultures. Bars represent % of selected options plotted to left ordinate. Scatter plot and error bars indicate mean values (based on scale below) and standard deviations, respectively, plotted to the right ordinate. Responses indicating functions as important (striped bars, 1) and very important (dotted bars, 2) are plotted above the upper abscissa. Responses indicating functions as somewhat important (bars with zig zag filling, −1), and very unimportant (bars with checker-board filling, −2) are plotted below the upper abscissa. Responses indicating importance as not clear (bars without filling, 0) are plotted above the lower abscissa. Numbers above the bars indicate response rate (n=25). Data source: Survey of farmers.*

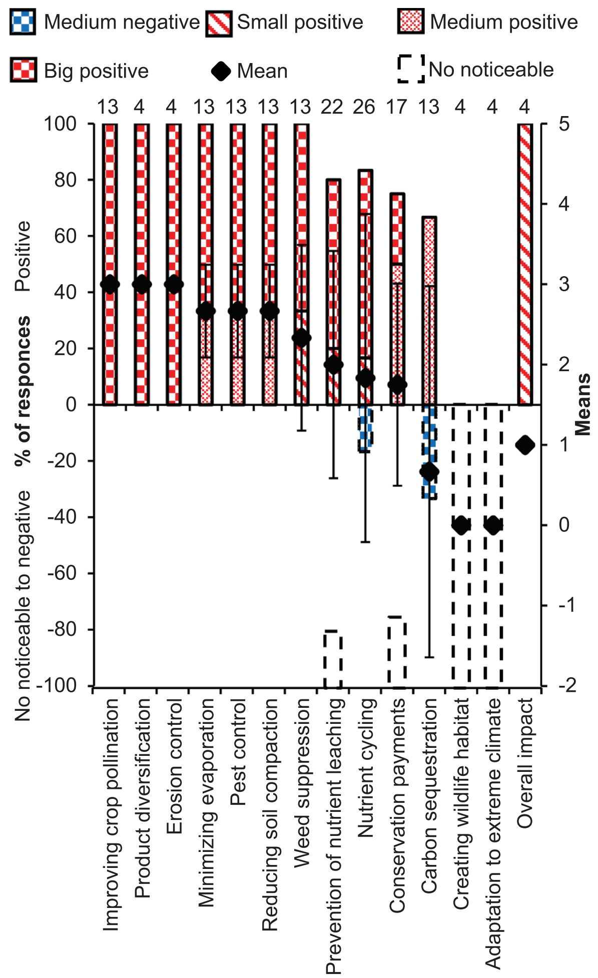

Figure 4. Results achieved with crop diversification.*Bars represent % of selected options plotted to left ordinate. Scatter plot and error bars indicate mean values (based on scale below) and standard deviations, respectively, plotted to the right ordinate. Positive results (dotted bars – big positive (3), stripped bars – medium positive (2), bars with checkboard filling – small positive (1)) are plotted above the upper abscissa. Negative results (medium negative – bars with zig zag filling (2)) are plotted below the upper abscissa. No noticeable results (bars without filling, 0) are plotted above the lower abscissa. Numbers above the bars indicate response rate (n=25). Options with zero responses (small (−1) and big negative (−2) categories, decreasing labor requirements, nursing, increase of aesthetic value) are not plotted. Data source: Survey of farmers.*

Enhancement of supporting and regulating services linked to resource conservation and biological control were the main goals for farmers in choosing to cultivate polycultures (Figure 2a). These were followed by goals to decrease negative impact of agricultural management on the environment and to increase long-term resilience. Alleviation of adverse environmental conditions was the least important function for growers, and polycultures

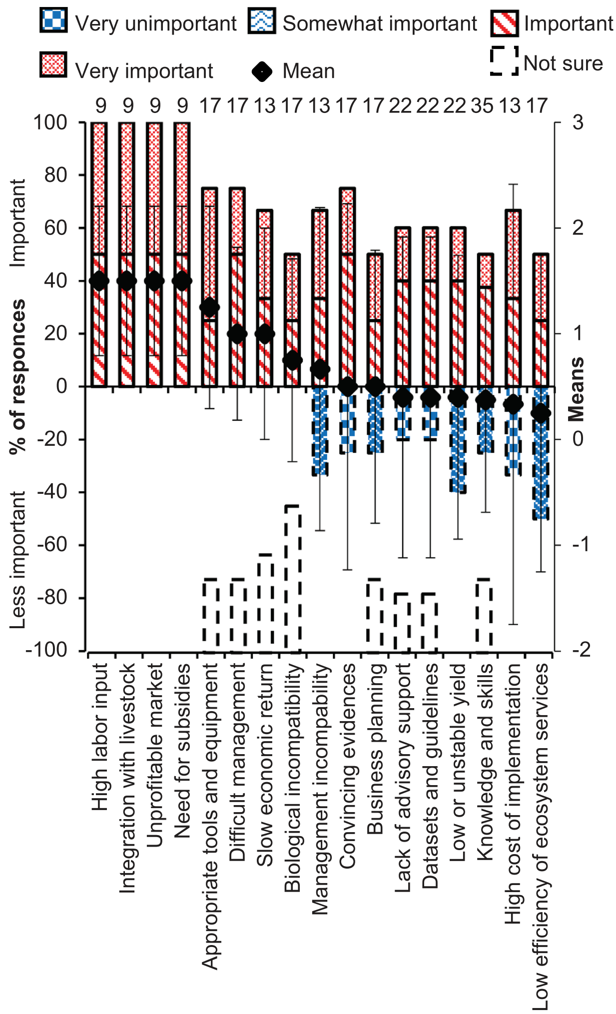

Figure 5. Constraints for crop diversification. *Bars represent % of selected options plotted to left ordinate. Scatter plot and error bars indicate mean values (based on scale below) and standard deviations, respectively, plotted to the right ordinate. Challenges reported as important (striped bars, 1) and very important (dotted bars, 2) are plotted above the upper abscissa, and challenges rated as well as somewhat important (bars with zig zag filling, -1) and very unimportant (bars with checker-board filling, -2) are plotted below the upper abscissa. Challenges where respondents were not sure about importance (bars without filling, 0) are plotted above the lower abscissa. Numbers above the bars indicate response rate (n = 25). Data source: Survey of farmers.*

were perceived as labor-intensive rather than labor-saving practices. Growers were interested in improving nearly the same functions in their existing polycultures (Figure 2b; Wilcoxon rank sum tests demonstrated no statistically significant differences, data not shown).

Farmers were able to meet most of their desired supporting and regulating functions with crop diversification (Figure 3). However, growers failed to meet some secondary functions, such as creation of wildlife habitats and adaptation to extreme climate conditions. Anecdotal evidence of negative impacts of crop diversification on nutrient cycling and carbon sequestration have also been recorded.

Challenges to crop diversification highly vary between individual growers, in particular regarding access to knowledge, information, and tools (Figure 4). Greater consensus was observed in terms of the importance of management and economic constraints, while regulations were not regarded as limits by farmers from the studied regions.

Databases of crop traits

Since grower-oriented databases reported both crop traits and functional characteristics familiar to growers, the latter have also been included in the analysis and referred to as traits, though these characteristics are mediated by varying and unspecified sets of plant traits. Traits which can serve as direct predictors of agroecological functions and environmental tolerances, were available for all specified agroecosystem functions in a combined database (Table S1). Individual traits have been reported for varying numbers of species; however, most functions can be defined by redundant traits, which increases database predictive capacity. However, the trait database contained medium to low numbers of species reports and thus low predictive capacity for root metrics linked to: nutrient and water absorption capacity (surface area, volume); crop impact on soil organic carbon (SOC) content; nutrient acquisition and accumulation traits, including carbon/nitrogen (C/N) ratio (also linked to mulch production, nutrient cycling, SOC content); growth temperature requirements, light use efficiency indicators, and floral morphology as predictor of attraction of different groups of pollinators.

We retrieved 2,491 trait records with 32,170 observations from TRY database. Of these trait records, 71% are quantitative, but only 76% of them had normal distribution across all focus plant species having at least 20 trait observation reports (where the Shapiro-Wilk test has the highest predictive power (Statistics Kingdom 2017)).

Systematic literature review

The majority of publications on integration of spice and aromatic crops with vegetables report results from *in vitro* experiments followed by pot or greenhouse experiments, field trials with no repetitions, field trials with repetitions, and field trials in various pedoclimatic conditions (Figure 5a). Researchers studied plant interactions using mainly extracts

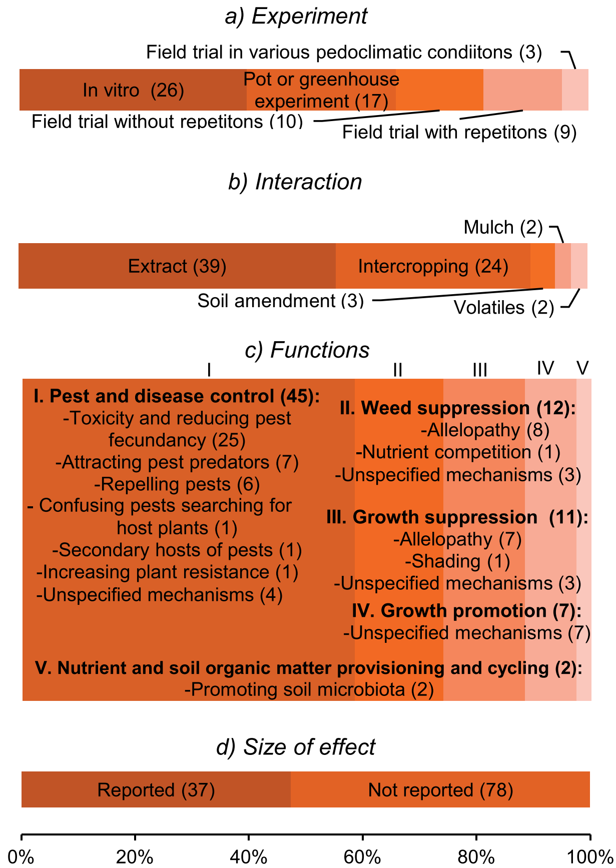

Figure 6. Published reports on the use of spice and aromatic plants in vegetable polycultures retrieved from 64 publications identified after systematic literature review.*Reports are categorized by experimental scale (a), type of interaction (b), agroecological functions studied and its prospective mechanisms (c), and availability of numerical data on the size of effect (d). Number of reports exceed the number of included publications. Data source: literature review.*

followed by intercropping, soil amendments, mulch, and volatiles (Figure 5b).

Altogether, the database includes 413 observations of positive, 67 of negative, and 2 of neutral interactions. Most reports relate to pest and disease control followed by weed suppression, growth suppression of intercropped plants, and growth promotion (Figure 5c). Prospective mechanisms can be pinpointed for 78% of reports, and the size of effect can be identified in 47% of reports (Figure 5d).

Authors of analyzed publications used a variety of synonymic keywords. The optimal keywords have been identified in each synonymic row based on both frequency of use and topic coverage (Table S2).

Data complementarity assessment with the polyculture design tool

Our database constructed from reviewed literature included 548 unique spice and aromatic crops and 36 vegetable and other potential companion crops, 76 weed and other plausible nuisance plant species and 177 pests and diseases potentially suppressed by specific spice plants, and 7 biocontrol organisms positively influenced by certain spice and aromatic plants. Observational reports also included companions for 22 vegetable crops reported by growers (who selected among 9 spatiotemporal crop association options) and known companions for 45 crops and known incompatible crops for 31 crops retrieved from grower-oriented databases. Incorporating all these data sources, the combined trait database distributes crops among 8 functional groups by plant architecture and growth characteristics, 12 groups by nutrient cycling, 5 groups by susceptibility to pests and diseases, and providing resources to pollinators, 2 groups by the integration with livestock, and 1 group by additional intercropping considerations (Table S3). Such grouping reflects the number and possibilities of crop combinations with different trait levels to increase functional complementarity or with similar trait levels to enhance ecological facilitation (*e.g.*, mycorrhizal association). Data integration from different sources into the polyculture design algorithm is shown on Figure 6.

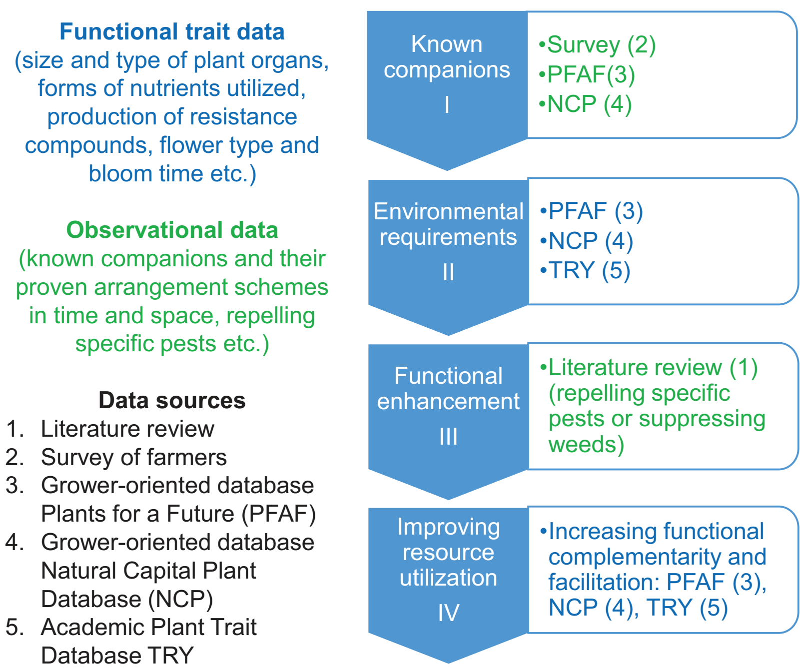

Figure 7. Outline of a beta version of a polyculture design algorithm.*1. Systematic literature review on the use of spice and aromatic crops in vegetable polycultures. 2. Survey of vegetable farmers practicing community-supported agriculture.*

Complementarity between crop data pooled from different sources was also demonstrated using potato and disease resistance as examples (Table S4). The expert survey reports two crops and three crop groups for possible rotation with potato, and grower-oriented databases list three additional compatible crops. The literature review features 16 crops for controlling 3 specific potato pests and 1 disease, and grower-oriented databases complement this list with 6 additional crops for controlling 2 pests. Potentially incompatible crops include 5 and 1 crop serving as secondary hosts to potato pests from the literature review and grower-oriented databases, respectively, 5 crops with potential for growth suppression from the literature review, and 10 unspecified incompatible crops from grower-oriented databases. Altogether, data sources mentioned above list 25 companion crops, 4 incompatible crops, and 6 crops with dual function (hosts to potato pests revealing suppressive potential to certain potato diseases) featuring companions for controlling 3 potato pests and 1 disease. The combined trait database includes 32 traits potentially linked to pest and disease resistance in a polyculture context: 8 from TRY database, 17 from NCP database, and 7 from PFAF database (Table S1). 68% of these traits might serve as direct predictors of crop resistance, and 64% of traits compose four redundant groups ranging from 2 to 14 traits per group.

Discussion

Our research sheds light on the structure of the vegetable cropping systems utilized by German-speaking CSA farmers confirming our assumption that the majority of these growers (92%) practice multispecies (>20) diversified cropping. Being located in several climate zones, they apply a broad range of system organization principles and practices from organic agriculture, permaculture, and biodynamic agriculture approaches, as well as academic research. This high diversity of underlying approaches, pedoclimatic conditions, and CSA scales (ranging from 0.5 to 450 ha and from 35 to over 2,000 CSA members) makes the organized and rapidly growing (from 19 to 368 CSA between 2011–2021) network of CSA a convenient group for participatory design of sustainable cropping systems (Netzwerk Solidarische Landwirtschaft e.V 2020). In addition, comparing to box schemes popular in the US CSA, German-speaking and European CSA have more flexible production systems (and hence more opportunities for experimentation) as the quantity and quality of the share depend on the outcome of the harvest (Kraiß and van Elsen 2009). Thus, CSA also deliver valuable contributions to diversifying the structures for food supply to cities, as city regional food strategies point out (e.g. AG.URBAN 2018).

The surveyed farmers prioritized crop diversification goals that were most directly related to the practicalities of on-farm crop management. Notably, they assigned lesser importance to larger-scale agroecological systems goals that are often generated by societal sustainability perspectives, such as carbon sequestration and related conservation payments, and aesthetic value. This seems to be an indication that the link between societal and political demands for sustainability, on the one hand, and the potential of polyculture cropping systems to transform agriculture, on the other hand, is not yet fully perceived. Despite this lack, CSA farmers assessed those categories of goals as gaining more relevance in the future.

While most crop polyculture schemes practiced by German-speaking CSA farmers were effective in providing multiple desired agroecological functions contributing to sustainability, the perceived level of these functions is often suboptimal. Positive but suboptimal performance of polycultures was also demonstrated in a metanalysis by Landis et al. (2005). This analysis reports 53% increase in populations of natural enemies of crop pests and 60% increase in pest mortality. A polyculture design approach aimed at increasing functional trait diversity (*e.g.* accessing different chemical forms of nutrients, or resource acquisition staggered in time and space) rather than simple increase in species number can potentially improve performance of crop polycultures (Perović et al. 2018). Yet common polyculture design approaches, for example increasing crop stand structural complexity (Gontijo et al. 2018; Jones and Sieving 2006) or provisioning abundant floral resources (Perović et al. 2018) may sometimes have negative impacts on pest control. Therefore, early and comprehensive integration of observational data into trait-based polyculture design models is essential for model verification and refining.

While survey respondents typically succeeded in medium to good level achievement of their few primary goals linked to crop production processes, they failed to reach desired multifunctionality with their polycultures. Secondary goals related to increasing environmental and economic sustainability of production systems may naturally receive less attention, as benefits from these agroecosystem services are more difficult to observe and evaluate. Hence polyculture modeling tools may play an important role in simultaneous visualization of multiple outputs as well as in educating growers on simple procedures for rapid ecosystem function assessment (Meyer, Koch, and Weisser 2015).

Many growers acknowledged access to knowledge, datasets, and convincing evidence as constraints to crop diversification. Digital polyculture design tools might operate large amounts of data and several algorithms. Therefore, they can potentially help growers to increase productivity of polycultures as well as to improve multifunctionality of agroecosystems. Such tools (e.g. Midwest Cover Crop Council 2006) typically incorporate individual preference patterns of tradeoffs between desired agroecosystem services to optimize polyculture multifunctionality under specified environmental constraints. Increasing multifunctionality and stabilizing mixture performance under variable conditions usually requires increasing functional redundancy and species number (*e.g.*

60% higher hay yield in species-rich (25–41 plant species) than species-poor (6–17 species) sowings (Bullock et al. 2001). This is opposed to uni-functional system optimization which is peaked at low species diversity and is often composed of only a few polyculture components with the highest individual biomass production (reviewed in Perović et al. 2018).

Polyculture design is routinely aimed at increasing positive interactions (complementarity and facilitation) and decreasing negative interactions (competition). However, in complex, multi-functional systems, tradeoffs are often not only unavoidable, but also sometimes necessary. For example, accepting a certain level of root competition can aid in niche stratification and thus better resource utilization in mature polyculture systems (Hauggaard-Nielsen, Ambus, and Jensen 2001). While visualizing and optimizing tradeoffs is a complex task, a simple approach can be grounded in assessing the relative weight of potential positive and negative interactions in each crop pair and analyzing their management compatibility (Brodt, Fontana, and Archer 2020).

For mechanistic modeling of crop interactions we retrieved crop trait values from databases that report average trait level as well as from those that contain data from individual observations. In the latter case, trait value distribution other than normal may be linked to either operational errors (both from false reports in the database and failure to algorithmically retrieve correct trait values from the database), or trait plasticity – varying level of study trait expression under different environmental conditions (which can have important implications in both designing polycultures and in studying trait plasticity). Alternatively, recording trait level under variable environmental conditions and averaging multiple trait observations could partly compensate for the impact of trait level plasticity.

The present study combined mostly qualitative trait data from grower-oriented databases with mostly quantitative data from academic trait database demonstrating the utility and complementarity of various information sources. Increasing the number of trait databases will both increase redundancy, where individual agroecosystem services are the functions of numerous direct and indirect predicting traits. It will also allow constructing a more complete functional dataset for the target crop pool, as no database utilized in this study contained complete reports for all target crops and traits.

Possible options of crop arrangement in space and time can be deduced from both survey reports and analysis of crop functional traits. In particular, intercropping benefits linked to mycorrhizal nutrient transfer and nutrient solubilization require direct root interactions; nutrient facilitation from residue mineralization requires temporal synchronization between nutrient release and demand by the subsequent crop. Efficient distance of interactions is characteristic of biological control services and depends on mobility of biological or chemical agents and properties of a medium (*e.g.*, flying distance of pollinators and biocontrol animal organisms is a function of their body size and vegetation cover, Perović et al. 2018). In addition, competition can be reduced by staggering planting time and growing periods and increasing distance between units of different crops. Though simultaneous intercropping was the most preferential crop combination method for survey respondents, the use of a computational tool can potentially help to increase performance of polycultures offering a wider range or more feasible options of crop integration in space and time (*e.g.,* Damour et al. 2018).

While the survey of academic publications provided reach and an easily accessible source of observational data for designing crop polycultures, this source remains underutilized as an integral part of tools for practitioners as well as for science. The lack of a common structure in reports complicates development and application of data mining software. We suggest that researchers utilize our recommended keywords for facilitating publications search. Also, we advise presenting in abstracts the composition of studied cropping systems, the size, and units of noteworthy effects. Our systematic literature review of vegetable polycultures with spice and aromatic crops demonstrated the lack of field trials with repetitions over time. Therefore, researchers can utilize our dataset to define future research directions for upscaling polyculture systems.

Combination of trait matching and observational evidence collected from both literature and directly from growers would increase the predictive power of the polyculture design tool in achieving desired agroecosystem functions. In our research, grower-oriented databases and further systematic literature review complemented data reported by growers, allowing for a more tailored polyculture design approach by utilizing proven companions to enhance desired agroecosystem functions, such as controlling specific pests. A trait-based approach allowed further optimization of crop functional complementarity and facilitation and hence the possibility to improve polyculture productivity and resource utilization beyond reported crop combinations.

Pooling information from several sources would allow tool developers and/or users to identify and ignore faulty reports by comparing information between the sources. In addition, our tool compares sources and visualizes potentially incompatible crops after each round of polyculture expansion. Further collection of observational information from tool users for miscellaneous crop reports would allow us to define which traits best predict individual agroecosystem functions. At the same time, constructing a dataset from multiple sources increases the workload, requires higher algorithmizing thus making it difficult or impossible to check errors.

Our polyculture design tool has been launched in test mode to identify and correct possible faults, reveal reliable predictors in each group of redundant traits, and to pool additional observational data from growers for improving tool performance. Our tool allows designing polycultures around defined vegetable and spice and aromatic crops, as well as for defined sets of environmental conditions.

While the trial version of our polyculture design tool can be already utilized by agriculture extension workers and farmers, it should be noted that the amount and the nature of observational data that we collected does not allow a tailored design of polyculture systems for specific pedoclimatic conditions. However, this functionality is partially achieved using crop trait data in our tool. As the majority of reviewed studies report effects of plant extracts evaluated *in-vitro*, these effects may not be observed in polycultures containing spice and aromatic crops mentioned in the reports. In addition, the mode of spatial and temporal crop integration in polycultures is important for maximizing facilitative and minimizing competitive interactions, as well as for crop management compatibility. This information is currently based on farmer reports collected for a limited number of crops in our tool.

As for all polyculture design tools, reported or modeled facilitative interactions between crops may not be efficient enough to achieve the desired level of agroecosystem functions in polycultures. Therefore, additional strategies (*e.g.*, application of microbial biopreparations or enriched plant extracts possessing antagonistic properties toward the pests of concern) may be necessary to achieve desired functionality in agroecological systems.

Structured systematic knowledge needed for exploiting the potential of polyculture cropping in agroecology can be generated and framed into a design tool if co-developed by scientists and practitioners. However, contributions and functional requirements will differ between these stakeholders.

Further tool development requires application of mathematical modeling for multifunctional polyculture optimization, for example, evolutionary optimization algorithms (Dury et al. 2012). It will also require developing mathematical links between several traits when modeling functions and revealing species functional clusters or constructing functional profiles to better visualize species compatibility. Furthermore, it will require visualizing tradeoffs between the services of interest and dis-services of concern by linking them to underlying processes and crop traits (Damour et al. 2014; Damour, Guérin, and Dorel 2016). Complex modeling also requires linking to existing models developed for optimization of particular processes. Such models might include those for light use efficiency (Evers et al. 2019), pollination (M'Gonigle et al. 2017), weed control (Bohan et al. 2011; Colbach et al. 2017), and particular cropping systems (*e.g.*, cover crops (Northeast Cover Crops Council 2020), crop rotation (Bachinger and Zander 2007; Naudin et al. 2015), and agroforestry (Dufour et al. 2013; Talbot and Dupraz 2012). A major challenge will be to integrate this information and develop both observational and trait-dependent rules to support the spatial and temporal synchronization of polyculture cropping. Finally, tool development would also benefit from algorithmizing information collection from academic and extension reports in connection with crowdsourcing from both academics and practitioners (Kanter et al. 2018).

Conclusions

By processing a large amount of data and utilizing a growing number of crop matching principles, polyculture design algorithms can play an important role in helping farmers and agricultural extension specialists to increase productivity and multifunctionality of crop polycultures. This would support enhancing competitiveness of diversified cropping systems, reducing the need for environmentally problematic and expensive external inputs, and increasing the spread of sustainable agriculture. These algorithms can better integrate services and benefits toward meeting societal challenges that go beyond individual farm considerations but underline the value of transformation toward agroecological systems to generate public goods and benefits.

While the majority of polyculture design tools utilize mostly observational or functional trait-based information (Malézieux et al. 2009), our work stands as a proof of concept demonstrating the feasibility and benefits of combining these two approaches as well as from pooling data from both academic and grower-oriented sources. Further research will be focused on assessing and improving tool robustness, as well as on developing additional functionality important for growers, in particular assessment of crop management compatibility, potential profitability, and crop arrangements in space and time.

In parallel, our polyculture design tool can be utilized as a decision support mechanism in co-developing and testing polycultures with growers. Future research can combine *in silico* participatory design of crop polycultures, ideally in a gamified manner involving growers, extension specialists, and researchers. Citizen science research would allow testing designed polycultures under a range of pedoclimatic conditions and stepwise optimization of crop arrangements. On-station research would complement citizen science trials by conducting a wider set of instrumental measurements. Ultimately, this undertaking would benefit from an international consortium that combines the strengths of farmers and farmer associations from among different regions, agricultural extension specialists, crop researchers, and biomathematicians.

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Code availability

The codes generated during the current study are available from the corresponding author on reasonable request.

Consent to participate

Survey and interview respondents provided consent to participate in this study and to publish their anonymized data in scientific papers.

Consent for publication

Survey and interview respondents provided consent to publish their anonymized data collected during this study in scientific papers.

Data availability statement

The datasets generated during and/or analyzed during the current study are incorporated into Google Drive version of the polyculture design tool accessible at https://docs.google.com/spreadsheets/d/1JzS68FWbju8po9K-e-V5-6UsUjE3YXYdynLdrWyoMFs/edit?usp=sharing. Dataset generated after the systematic literature review is additionally deposited into the Bonares Repository (Ardanov et al. 2023).

Ethics approval

Template of a consent form developed by the Leibniz Centre for Agricultural Landscape Research (ZALF) e. V for research with human participants was utilized and adapted for study purposes.

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