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Designing high-performance crop polycultures for community-supported agriculture

[Developing beta-version of design algorithm for vegetables and leafy greens]

Pavlo Ardanov

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Contents

Preface

Efforts to spread knowledge-intensive biodiversity-based agriculture require specific scientific recommendations, and these are often too general (Duru & Therond, 2015). The combined efforts of multidisciplinary researchers and practitioners are needed to design low-input, scalable, high-yielding polyculture systems, which will be environmentally-tailored and focused on biodiversity restoration.

1. Introduction

Agricultural systems cover approximately 40% of the land surface of the Earth and thus have a significant biospheric impact (Lescourret, Magda, et al., 2015). This impact is likely to increase as the population grows by an additional two billion by 2050 and requires 30% more food production globally than is produced at present (Wezel et al., 2014). Contemporary industrial agriculture has numerous drawbacks due to its dependence on intensive management and on the availability of scarce and non-renewable resources, and consequently negative impact on ecosystems.

Therefore, progress towards a more low-risk ecologically functional agriculture is required (Altieri et al., 1983), one that will be compatible with ecosystem resilience to climate change (Lescourret, Dutoit, et al., 2015; Wezel et al., 2014). 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) as well as having multiple environmental benefits (Daryanto et al., 2018).

Field performance of crop polycultures is often context specific, and multiple agronomic, socioeconomic, and environmental objectives need to be considered. Therefore, successful design of diversified cropping systems requires both improved conceptual knowledge and participatory development.

Community-supported agriculture (CSA) is based on direct linkage between farmers and customers, where farmers receive guaranteed secure market and upfront investment, while subscribed customers benefit from healthy, diverse, and affordable seasonal food. CSA belongs to civic agriculture and is aimed at strengthening a sense of community, supporting local economy by small-hold ecological producers and on reducing food mileage. It is also a part of a food sovereignty movement aimed at returning control over corporate and globalized food system to communities thus increasing food security.

Long quarantine due to COVID-19 pandemic has strongly hit Ukrainian farmers, in particular micro-, small, and medium-sized producers who sold their produce in farmers markets (80% of agriculture produce in Ukraine (Зверева, 2020)) and to restaurants. Pandemic proved risk efficiency of CSA (Shilton, 2020), and a growing number of farmers and citizens in the Western countries are shifting towards CSA, where direct linkage and mutual support and responsibility increase resilience. Productivity optimization in highly diverse CSA farms growing numerous species of fruits, vegetables, and greens to meet customers demand is challenging and knowledge intensive. At the same time, higher diversity of plant species increases the number of ecological niches, which can further increase the number of associated species (including native and rare species) (Liu et al., 2018), and ecosystem services provided by CSA farms, including carbon sequestration. In particular, it can transform the agriculture sector from one of the biggest greenhouse gases emitters (from 10 to 35% of total greenhouse gas emissions in Europe (Eurostat, 2015)) to efficient CO_2 sinks capable of conserving up to 0.5–1.5 Pg C annually (Milla et al., 2017), when preference is given to no-till, functionally assembled, perennial polycultures. Germany with 286 existing and nearly 100 emerging CSAs (*Netzwerk Solidarische Landwirtschaft*, n.d.) provides a good opportunity to gain insights on practice, experiences, beneficial conditions, and limitations of diversified production of vegetables and greens to improve the agronomic performance in this system, as well as to provide recommendations for introducing this model in Ukraine.

The **aim** of the proposed research is to promote diversified farming by providing recommendation on commercially feasible crop polyculture with vegetables, leafy greens, and spice and aromatic plants for cold temperate climate. This will be achieved by developing decision support tool for vegetable growers that will combine trait-based and participatory design approaches by utilizing information collected from databases, survey, and literature review. Trait-based approach is based on predicting species interactions as a function of the physiological, morphological, chemical or phenological characteristics of organisms (Martin & Isaac, 2015).

Research project was complemented by a conference "Launching community-supported agriculture in Ukraine" organized for promoting this model among Ukrainian farmers and customers, establishing an international peer-support groups for farmers, and launching regional CSA initiatives in Ukraine.

2. Materials and methods

2.1. Farmers survey

This study used semi-structured, open-ended surveys and interviews. 269 vegetable growers were selected among German, Austrian, and Swiss farmers registered on the website of the German CSA association ((*Netzwerk Solidarische Landwirtschaft*, n.d.). Growers were contacted by Email and offered either to participate in an online survey in German or in English or in an individual video interview in English conducted by lead researcher. 23 growers participated in survey and 2 - in the interview. 23 participants out of 25 had previous experience with cultivating crop polycultures. 41% of participants identified themselves as "Biodiversity-based or permaculture farmers", 53% - as "Certified organic farmers", 12% - as "Certified biodynamic farmers", 0% - as "Conventional farmers", 18% - as "Researchers", and 0% - as "Agriculture consultants or permaculture designers". Average plot size or respondents was 9.47 ha±10.13 ha ranging from 2.00 to 21.00 ha. And on average polyculture cropping systems occupied 36.64% of farm plot area ranging from 2.22% to 100.00%.

Both survey and interview guide included questions about observed benefits and constraints of polyculture practices, motivations 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 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 to provide recommendations on establishment and management of particular crop combinations for peer growers.

All responses were categorized into three broad topics: Motivation and gained results, Future directions and constraints, and Crop arrangement in time and space. In its turn, motivation was categorized into following categories: Improving soil fertility, Improving crop pollination and biocontrol, Creating benign physical environment for crops, Improving farm economy and work performance, and Agroecosystem services not linked to crop production. While constraints were categorized as following: Poor performance of polycultures, Management constraints, Economic and regulatory constraints, and Access to knowledge and information. The number of responses was tallied for each category and subcategory.

2.2. Databases of crop traits

List of most popular cash crops by German CSA farmers was constructed based on 8 randomly picked farms from SOLAWI website that report crop lists on their online profiles. Constructed crop list included 38 vegetable crops and 39 leafy green crops where 38% of crops from this combined group were sold on at least 3 farms. When available, crop trait information for selected crops was retrieved from two "grey" databases referred as PFAF (PFAF, n.d.) and NCP (*Natural Capital Plant Database*, n.d.) using custom web scrapping algorithms. As well as from research database TRY (Fraser, 2020) where public data were requested.

160 traits reported in TRY database for 14 selected crops each representing different family were identified as predictors of agroecosystem services in crop polycultures and grouped into 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, Human usage. Each of these categories were further divided into relevant subcategories. 62

traits and sections from PFAF database and 86 from NCP database were also included into respective categories.

Predictive capacity of constructed trait database for each agroecosystem service was assessed by the number of species and number of observation reports for individual trait. Traits reported for minimum 3 species were utilized in our polyculture design algorithm.

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

2.3. Systematic literature review

Systematic literature review of experimental and review publications was performed to identify aromatic crops as reported or prospective companions in vegetable cultivation. 64 publications with reports from temperate climate were retrieved from ScienceDirect Elsevier's platform of peer-reviewed literature using search query that combined synonyms for spice and aromatic plants with synonyms of polyculture cultivation systems and key polyculture terms or with synonyms of biological control.

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 following categories: Nutrient and soil organic matter provisioning and cycling, Pest and disease control, Weed suppression, Suppression of intercropped plant, Growth promotion of intercropped plants. The size of effect, measurement units, and prospective mechanisms were reported for each category whenever available.

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

2.4. Polyculture design tool

Beta version of polyculture design tool was produced on Google sheets platform and can be accessed by following link: https://docs.google.com/spreadsheets/d/1JzS68FWbju8po9K-e-V5-6UsUjE3YXYdynLdrWyoMFs/edit?usp=sharing. Initially algorithm operate with up to 5 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 "Zones" according to user-specified environmental requirements, and later each polyculture is designed individually. In addition to companions reported in databases, user can include spice and aromatic crops from our systematic literature review database (different selection options available: as companions of selected crops, for biological control of defined pests or for attracting defined pest predators, for control of defined weed species). Polycultures can be also complemented with crops reported as companions by survey participants, reported spatial and temporal crop arrangement is displayed for selected crops. Finally, complementarity in polycultures can be increased stepwise by preferred order of significance in following categories: Plant architecture and growth cycle, Nutrient cycling, Pest, disease resistance and pollination, Companion cropping and integration with livestock.

Whenever database report different levels of particular traits, most frequent options are automatically selected, or 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, user can intentionally include companions with potentially incompatible environmental requirements or keep crops with reported incompatibility into designed polycultures.

3. Results

3.1. Survey results

Surveyed farmers managed diverse cropping systems with on average 21±14 vegetable species, 35±10 leafy greens species, 7±4 cover crop species and 2±1 livestock species. 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.

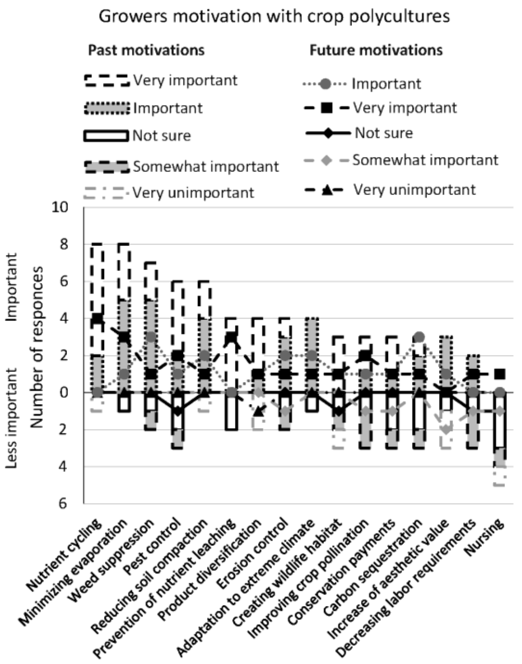

Figure 1: Motivations for growers to achieve with crop polycultures.

Past motivations – functions that growers wanted to improve when designed existing polycultures. Future motivations – functions that growers want to improve in existing polycultures or to achieve with transitioning to polycultures. Responses indicating functions as important and very important are plotted above X axis while responses indicating function importance as not clear, somewhat important, and very unimportant are plotted below X axis.

Enhancement of supporting and regulating services linked to resource conservation and biological control were the main motivation for farmers to cultivate polycultures (**Fig. 1)**. These were followed by motivations to decrease negative impact of agroecosystems on environment and to increase long-term resilience. Facilitation was the least important function for growers, and polycultures were perceived as labor-intensive rather than labor-saving practices. Growers were interested to improve nearly the same functions in their existing polycultures.

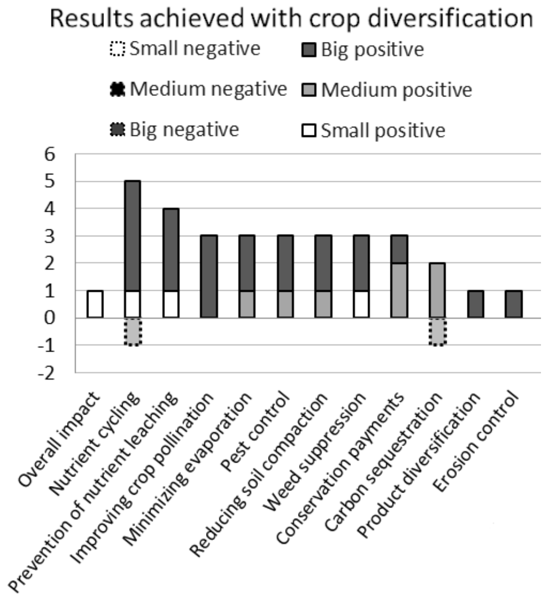

Figure 2: Results achieved with crop diversification.

Positive results are plotted above X axis and negative results are plotted below X axis.

Farmers were able to meet most desired functions with crop diversification, in particular improvement of nutrient cycling and prevention of nutrient leaching (**Fig. 2**). However, growers failed to meet some secondary functions, such as creation of wildlife habitats and adaptation to extreme climate conditions. And anecdotal evidences of negative impact of crop diversification on nutrient cycling and carbon sequestration have been also recorded.

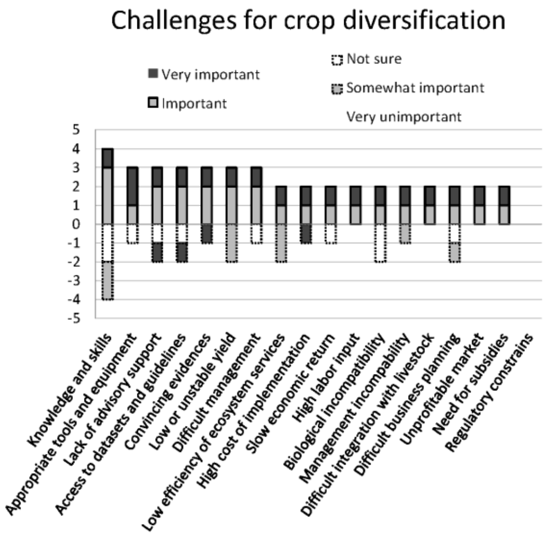

Figure 3: Constraints for crop diversification.

Challenges reported as important and very important are plotted above X axis and challenges where respondence were not sure about importance as well as somewhat important and very unimportant are plotted below X axis.

Challenges to crop diversification highly vary between individual growers, in particular regarding access to knowledge, information, and tools (**Fig. 3**). Higher consensus observed in terms of important role of management and economic constraints. And regulations were not regarded as limits by farmers from studied region.

3.2. Databases of crop traits

Traits which can serve as direct predictors were available for all specified agroecosystem functions in a combined database (**Table S1**). Individual traits have been reported for varying number of species, however most functions could be defined by redundant traits which increases database predictive capacity. However, trait database contained medium to low number 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 different groups of pollinators.

71% of traits retrieved from TRY database were quantitative. Normal distribution is observed for 76% of all quantitative traits across all focus plant species having at least 20 trait observation reports (where Shapiro-Wilk test has highest predictive power (Statistics Kingdom, n.d.)).

3.3. Systematic literature review

Majority of publications on integration of spice and aromatic crops with vegetables report results from *in vitro* experiments (50%) followed by pot or greenhouse experiments (31%), field trials with no repetitions (19%), field trials with repetitions (17%), and field trials in various pedoclimatic conditions (6%). Researchers studied plant interactions using mainly extracts (62%) followed by intercropping (37%), soil amendments (5%), mulch (3%) and volatiles (3%).

Majority of reports relate to pest and disease control (85%) followed by weed suppression (22%), growth suppression of intercropped plant (20%), and growth promotion (11%). Size of effect can be identified for 47% of all reported functions in total.

Authors use variety of synonymic keywords in their publications. The optimal keywords have been identified in each synonymic rows based on both frequency of use and topic coverage (**Table S2**).

3.4. Polyculture design tool

Internal tool testing revealed incomplete and incorrect reports for some traits. Therefore, users' feedback will be collected to identify and later correct possible faults when developing subsequent tool version having more user-friendly interface. Short version of redesigned survey was incorporated into the tool to update report database.

4. Discussion

Our results demonstrated that while most crop polycultures are capable to serve desired agroecological functions, the level of these functions is often suboptimal. Growers also failed to reach desired multifunctionality with their polycultures. Positive but suboptimal performance of polycultures was demonstrated in metanalyses, e.g., 53% increase in populations of natural enemies of crop pests and 60% increase in pest mortality (reviewed in Landis et al., 2005). Design approach aimed at increasing functional trait diversity (e.g. different chemical forms of nutrient, or resource acquisition staggered in time and space) rather 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 complicity (Gontijo et al., 2018; Jones & Sieving, 2006) or provisioning abundant floral resources (Perović et al., 2018) may have dual impact on pest control. With sufficient computational power for multifunctional system optimization and evidence database polyculture design tool can help growers to improve performance of their polycultures. Such tools typically incorporate user-defined level or tradeoff 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. This is opposed to unifunctional system optimization which is peaked at low species diversity and is often contributed to a few most productive polyculture components (reviewed in Perović et al., 2018). Polyculture design is routinely aimed at increasing positive interactions (complementarity and facilitation) and decreasing negative impacts (competition). However, accepting certain level of root competition can aid in niche stratification and thus better resource utilization in mature systems, as demonstrated for both annual. e.g. pea-barley (Hauggaard-Nielsen et al., 2001) and perennial, e.g. walnut-wheat (Wang et al., 2018) polyculture systems.

Possible crop arrangements in space and time can be partly defined by crop functional traits and thus incorporated into design tool. In particular, intercropping benefits linked to mycorrhizal nutrient transfer and nutrient solubilization require direct root interactions while nutrient facilitation from residues mineralization requires synchronization between nutrient release and demand by subsequent crop. Efficient distance of interactions is characteristic to biological control services and depends on mobility of biological or chemical agent and properties of a medium (e.g. flying distance of pollinators and biocontrol organisms is a function of their body size and vegetation cover). And competition can be reduced by staggering planting time and growing periods and increasing distance between units of different crops. Same logic can be applied for developing service crop systems both as undercrops and as components of rotation cycles. 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. It should be based on assessing the relative weight of potential positive and negative interactions in each crop pair and on their management compatibility (Brodt et al., 2019).

Combination of trait matching and empirical evidences collected from both literature and directly from growers would increase predictive power of polyculture design. Both recording trait level under variable environmental conditions and averaging multiple trait observations could partly compensate for the impact of trait level plasticity. Present study combined mostly qualitative trait data from "gray" databases with mostly quantitative data from academic trait database demonstrating the utility and complementarity of various information sources. Yet this also increase the risk of false or uncomplete individual reports. 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 more complete functional dataset for target crop pool, as no database utilized in this study contained complete reports for all target crops.

At the same time, constructing dataset from multiple sources increases workload, requires higher algorithmizing thus making difficult or not possible error checks. We retrieved 2491 trait records with 32170 observations from TRY database with 71% of quantitative traits where only 76% of them had normal distribution. 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 TRY database) or trait plasticity (which can have important implication in both designing polycultures and in studying trait plasticity).

Polyculture design tool can be used as decision support mechanism in co-developing and testing polycultures with growers. Our tool allows designing polycultures around defined vegetable, leafy greens, and spice and aromatic crops, as well as for defined set of environmental conditions. Our beta version lacks sufficient assessment of crop management compatibility, potential profitability, and possible options for spatial and temporal crop arrangement (though later is partly incorporated from growers' reports). Such assessments can be conducted using participatory polyculture design setting, ideally in focus groups involving growers, extension specialists, and researchers. Citizen science research allows testing designed polycultures under the range of pedoclimatic conditions and stepwise optimization of crop arrangements. On-station research would complement citizen science trials by conducting wider set of instrumental measurements.

Further tool development requires application of mathematical modelling for multifunctional polyculture optimization, e.g., evolutionary optimization algorithms (Dury et al., 2012). As well as linking to existing models developed for optimization of particular processes (e.g., light use efficiency (Evers et al., 2019), pollination (M'Gonigle et al., 2017), weed control (BOHAN et al., 2011) and particular cropping systems (e.g., cover crops (Northeast Cover Crops Council, n.d.), crop rotation (Bachinger & Zander, 2007; Naudin et al., 2015), agroforestry (Dufour et al., 2013; Talbot & Dupraz, 2012)). As well as algorithmizing of information collection from academic and extension reports in connection with crowdsourcing (Kanter et al., 2018). We suggest researchers to utilize our recommended keywords for facilitating publications search as well. Also, we advise to present in abstracts the composition of studied cropping systems, the size, and units of noteworthy effects. Systematic literature review of vegetable polycultures with spice and aromatic crops demonstrated the lack of field trials with repetitions. Therefore, researchers can utilize dataset that we constructed to define future research directions for upscaling polyculture systems.

Abbreviations & Acronyms

PFAF *Plants for A Future database*

NCP *Natural Capital Plant Database*

TRY Plant Trait Database (academic)

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Supplementary materials

Table S1: Crop traits used for the polyculture design tool

Trait ID*	**Trait name**	**Direct / Indirect****	**Redundancy*****	**No of species******		**No of observations*******
	PLANT PHENOLOGY					
	Growth rate					
NCP	Growth Rate	Direct	A	65	High	
587	Plant growth rate	Direct	A	30	Medium	32
196	Species strategy type according to Grime	Direct	A	29	Medium	41
26	Seed dry mass	Indirect		48	High	1695
	Growing period					
NCP	Growing Season	Direct	A	65	High	
NCP	Seasonal Interest	Direct	A	63	High	
865	Budbank seasonality	Indirect	A	32	High	643
1013	Leaf photosynthesis photoperiodism: type	Indirect	A	5	Medium	6
1251	Plant vegetative phenology (leaf phenology)	Indirect	A	5	Medium	8
	Lifespan					
NCP	Life Span	Direct	A	65	High	
59	Plant lifespan (longevity)	Direct	A	47	High	540
NCP	Stand Persistence	Indirect	B	30	Medium	
1187	Stem longevity	Indirect	B	11	Medium	14
	MODULATION OF ENVIRONMENTAL CONDITIONS					
NCP	Soil Cultivator	Direct	A	9	Medium	
NCP	Soil Builder	Direct	A	3	Low	
NCP	*Reclamator*******	*Direct*	*A*	*2*	Low	
NCP	Erosion Control	Direct	B	6	Medium	
PFAF	*Soil stabilization*	*Direct*	B	*1*	Low	

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
NCP	*Water Purifier*	*Indirect*	*B*	*1*	Low	
NCP	*Toxin Absorber*	*Indirect*	*B*	*1*	Low	
NCP	Nurse	Direct	C	3	Low	
NCP	*Hedge*	*Indirect*	*C*	*2*	Low	
	PLANT ARCHITECTURE					
	Shoot architecture					
42	Plant growth form	Direct	A	49	High	3319
1188	Stem self-supporting	Direct	A	15	Medium	21
PFAF	Form	Direct	A	3	Low	
1206	Plant vegetative reproduction: pattern forming	Direct		9	Medium	14
NCP	Height, cm	Indirect	B	65	High	
3106	Plant height vegetative	Direct	B	47	High	1264
3107	Plant height generative	Direct	B	37	High	314
NCP	Spread, cm	Indirect		65	High	
9	Root/shoot ratio	Indirect		7	Medium	196
140	Shoot branching type; shoot branching architecture	Direct	C	32	High	126
1194	Tillering type	Direct	C	32	High	127
3	Leaf angle (inclination, orientation)	Direct	C	5	Medium	12
144	Leaf length	Direct	D	12	Medium	56
145	Leaf width	Direct	D	12	Medium	74
410	Leaf area per plant	Direct	D	5	Medium	53
	Root architecture					
65	Root type, root architecture	Direct	A	38	High	141
NCP	Minimum Root Depth	Direct	A	49	High	

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
6	Root rooting depth	Direct	A	11	Medium	80
NCP	Root Type	Direct	B	61	High	
1093	Root position along clonal growth organ	Indirect	B	32	High	126
814	Plant morphological adaptations: root metamorphoses	Direct	B	10	Medium	10
1089	Root surface area per root dry mass (specific root area)	Direct	C	6	Medium	37
1080	Root length per root dry mass (specific root length, SRL)	Direct	C	6	Medium	53
82	Root tissue density (root dry mass per root volume)	Indirect	C	6	Medium	198
1091	Root volume per root dry mass	Indirect	C	6	Medium	15
83	Root diameter	Direct	C	6	Medium	27
1489	Root length fraction in respective root diameter class (e.g., fine root length per total root length;	Direct	C	5	Medium	5
2062	Fine root (absorptive) length per absorptive fine root dry mass (specific absorptive fine root length	Direct	C	3	Low	5
9	Root/shoot ratio	Indirect		7	Medium	196
	NUTRIENT CYCLING					
	Soil organic carbon content					
84	Root carbon (C) content per root dry mass	Direct	A	5	Medium	214
2551	Belowground plant organ carbon (C)	Direct	A	2	Low	2

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
	content per belowground plant organ dry mass					
2039	Fine root (absorptive) carbon (C) content per absorptive fine root dry mass	Direct	A	1	Low	1
1055	Root carbon/nitrogen (C/N) ratio	Indirect	B	5	Medium	198
146	Leaf carbon/nitrogen (C/N) ratio	Indirect	B	9	Medium	147
2552	*Belowground plant organ lignin content per belowground plant organ dry mass*	*Indirect*	*B*	*2*	Low	*2*
197	Plant functional type (PFT)	Indirect	B	7	Medium	493
NCP	Groundcover	Direct	C	10	Medium	
PFAF	*Biomass*	*Indirect*	*C*	*2*	Low	
PFAF	*Green manure*	*Indirect*	*C*	*2*	Low	
PFAF	*Ground Cover*	*Indirect*	*C*	*1*	Low	
	Groundcover					
NCP	Mulch Maker	Direct	A	6	Medium	
47	Leaf dry mass per leaf fresh mass (leaf dry matter content, LDMC)	Indirect	A	31	High	834
775	Shoot carbon (C) content per shoot dry mass	Indirect	A	12	Medium	26
13	Leaf carbon (C) content per leaf dry mass	Indirect	A	10	Medium	246

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
700	Plant biomass and allometry: Plant dry mass	Direct	A	6	Medium	181
403	Plant biomass and allometry: Shoot dry mass (plant aboveground dry mass) per plant		A	5	Medium	428
PFAF	Biomass	Direct	A	2	Low	
146	Leaf carbon/nitrogen (C/N) ratio	Indirect	B	9	Medium	147
409	Shoot carbon/nitrogen (C/N) ratio	Indirect	B	6	Medium	29
39	Litter decomposition rate	Direct	B	3	Low	14
NCP	Groundcover	Direct	C	10	Medium	
PFAF	*Ground Cover*	*Direct*	*C*	*1*	Low	
	Soil microbial diversity and activity					
2799	Belowground plant organ debris decomposition rate constant	Indirect		2	Low	2
NCP	Fungal Types	Direct	A	25	Medium	
7	Mycorrhiza type	Direct	A	38	High	778
3370	Mycorrhiza status and microbial interactions	Direct	A	4	Low	4
1030	Mycorrhizal infection intensity	Direct	B	20	Medium	76
1433	Mycorrhizal colonization: classified fractions of root length that contain mycorrhizae	Direct	B	13	Medium	53
NCP	Bacteria-Fungal Ratio	Direct		7	Medium	
	Nutrient accumulation					

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
80	Root nitrogen (N) content per root dry mass	Direct	A	6	Medium	222
14	Leaf nitrogen (N) content per leaf dry mass	Direct	A	23	Medium	369
50	Leaf nitrogen (N) content per leaf area	Direct	A	21	Medium	340
339	Shoot nitrogen (N) content per shoot dry mass	Direct	A	13	Medium	28
1126	Shoot organic nitrogen (N) content per shoot dry mass	Direct	A	12	Medium	12
2547	*Belowground plant organ nitrogen (N) content per belowground plant organ dry mass*	*Direct*	*A*	*2*	Low	*2*
146	Leaf carbon/nitrogen (C/N) ratio	Indirect	A	9	Medium	147
2569	*Belowground plant organ carbon/nitrogen (C/N) ratio*	*Indirect*	*A*	*2*	Low	*2*
2035	*Fine root (absorptive) nitrogen (N) content per absorptive fine root dry mass*	*Direct*	*A*	*1*	Low	*1*
2057	*Fine root (absorptive) carbon/nitrogen (C/N) ratio*	*Indirect*	*A*	*1*	Low	*1*
NCP	*Nitrogen Scavenger*	*Indirect*	*A*	*1*	Low	
340	Shoot phosphorus (P) content per shoot dry mass	Direct	B	15	Medium	36
15	Leaf phosphorus (P) content per leaf dry mass	Direct	B	14	Medium	106

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
701	Shoot potassium (K) content per shoot dry mass			15	Medium	26
704	Shoot calcium (Ca) content per shoot dry mass			15	Medium	26
702	Shoot magnesium (Mg) content per shoot dry mass			15	Medium	26
1127	Shoot sodium (Na) content per shoot dry mass			14	Medium	24
NCP	Dynamic Accumulator	Direct	C	13	Medium	
PFAF	Dynamic accumulator	Direct	C	7	Medium	
NCP	Biomass	Indirect	D	7	Medium	
PFAF	Biomass	Indirect	D	2	Low	
PFAF	Green manure	Indirect	D	2	Low	
NCP	Compost	Indirect	D	2	Low	
NCP	Soil Builder	Indirect	D	3	Low	
	Nitrogen fixation					
8	Plant nitrogen(N) fixation capacity	Direct	A	41	High	347
NCP	Nitrogen Fixer	Direct	A	10	Medium	
PFAF	Nitrogen Fixer	Direct	A	6	Medium	
	CULTIVATION REQUIREMENTS					
	Habitat					
PFAF	Habitats	Direct	A	35	High	
PFAF	Range	Direct	A	35	High	
200	Species occurrence range: number of floristic zones	Direct	A	27	Medium	27
	Temperature requirements and tolerance					

Trait ID*	**Trait name**	**Direct / Indirect****	**Redundancy*****	**No of species******		**No of observations*******
PFAF	Frost tolerance	Direct	A	30	Medium	
865	Budbank seasonality	Indirect	A	32	High	643
1136	Species environmental indicator value according to Ellenberg: temperature	Indirect	A	16	Medium	25
PFAF	*Temperature min*	*Direct*	*A*	*2*	Low	
PFAF	USDA hardiness zone	Direct	B	30	Medium	
NCP	USDA Hardiness Zones:	Direct	B	65	High	
NCP	Cold Injury	Direct	B	34	High	
1136	Species environmental indicator value according to Ellenberg: temperature	Direct	C	16	Medium	25
PFAF	Optimum growth temperature	Direct	C	7	Medium	
PFAF	Annual temperature range	Direct	C	4	Low	
PFAF	*Tolerated temperature range*	*Direct*	*C*	*2*	Low	
PFAF	*Temperature min*	*Direct*	*C*	*2*	Low	
827	Species occurrence range: origin zonal	Indirect	D	42	High	77
825	Species occurrence range: climate type	Indirect	D	16	Medium	108
1140	Species occurrence range characteristics	Indirect	D	23	Medium	482
1130	Species environmental indicator value according to Ellenberg: continentality	Indirect	D	16	Medium	16

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
822	Species occurrence range: ecological occurrence range	Indirect	D	3	Low	6
	Soil requirements					
1133	Species environmental indicator value according to Ellenberg: nitrogen	Direct	A	24	Medium	61
PFAF	Soil fertility	Direct	A	53	High	
1138	Species nutrient requirements	Direct	A	18	Medium	47
NCP	Soil pH	Direct	B	63	High	
1134	Species environmental indicator value according to Ellenberg: pH	Direct	B	24	Medium	57
600	Species habitat characterization / Plant requirement: soil pH	Direct	B	3	Low	6
NCP	Soil type requirements	Direct	C	65	High	
593	Species habitat characterization / Plant requirement: soil texture	Direct	C	3	Low	9
	Tolerances					
NCP	Salt tolerance	Direct	A	46	High	
1135	Species environmental indicator value according to Ellenberg: salt tolerance	Direct	A	24	Medium	42
1254	Species tolerance to salt	Direct	A	10	Medium	19
1023	Plant containing salt glands	Indirect	A	4	Low	7
1038	Species tolerance to heavy metals	Direct	B	4	Low	6

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
3371	Plant species use for bioremediation	Indirect	B	4	Low	4
NCP	Drought tolerance	Direct		61	High	
NCP	Flood tolerance	Direct		61	High	
NCP	Wind Storm Damage	Direct		36	High	
NCP	Soil Compaction tolerance:	Direct		33	High	
NCP	Fire Damage	Direct		30	Medium	
NCP	Mowing tolerance	Direct		29	Medium	
	Light requirements					
NCP	Light requirements	Direct	A	65	High	
PFAF	Sun requirements	Direct	A	33	High	
1131	Species environmental indicator value according to Ellenberg: light	Direct	A	24	Medium	45
788	Plant light requirement	Direct	A	12	Medium	14
603	Species tolerance to shade	Direct	A	16	Medium	95
1013	Leaf photosynthesis photoperiodism: type	Direct	B	5	Medium	6
3117	Leaf area per leaf dry mass (specific leaf area, SLA or 1/LMA): undefined if petiole is in- or excluded	Indirect	C	29	Medium	562
3116	Leaf area per leaf dry mass (specific leaf area, SLA or 1/LMA): petiole included	Indirect	C	24	Medium	456
3115	Leaf area per leaf dry mass (specific leaf area, SLA or 1/LMA): petiole excluded	Indirect	C	21	Medium	257

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
3109	Leaf area (in case of compound leaves: leaflet, petiole excluded)	Indirect	C	18	Medium	78
3111	Leaf area (in case of compound leaves: leaflet, petiole included)	Indirect	C	16	Medium	96
3108	Leaf area (in case of compound leaves: leaf, petiole excluded)	Indirect	C	8	Medium	44
3112	Leaf area (in case of compound leaves: leaf, undefined if petiole in- or excluded)	Indirect	C	8	Medium	20
3110	Leaf area (in case of compound leaves: leaf, petiole included)	Indirect	C	7	Medium	166
3113	Leaf area (in case of compound leaves: leaflet, undefined if petiole is in- or excluded)	Indirect	C	7	Medium	27
410	Leaf area per plant	Indirect	C	5	Medium	53
53	Leaf photosynthesis rate per leaf area	Direct	D	20	Medium	641
40	Leaf photosynthesis rate per leaf dry mass	Direct	D	17	Medium	51
269	Leaf photosynthesis electron transport capacity (Jmax) per leaf area (Farquhar model)	Direct	D	9	Medium	36
271	*Leaf photosynthesis light use efficiency (LUE)*	*Direct*	*D*	*2*	Low	*12*
10	*Leaf light absorption (extinction)*	*Direct*	*D*	*1*	Low	*1*
3380	Leaf photosynthesis drawdown of CO2 concentration from	Indirect	E	6	Medium	15

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****	No of observations*****
	intercellular airspace to chloroplast				
185	*Leaf photosynthesis carboxylation capacity (Vcmax) per leaf dry mass (Farquhar model)*	*Indirect*	E	*2* Low	*15*
22	Leaf photosynthesis pathway	Indirect		44 High	995
	WATER USE EFFICIENCY				
NCP	Soil moisture requirements	Direct	A	65 High	1
PFAF	Water requirements	Direct	A	35 High	
1132	Species environmental indicator value according to Ellenberg: moisture	Direct	A	24 Medium	48
599	Plant moisture use type	Direct	A	3 Low	3
602	Species habitat characterization / Plant requirement: precipitation	Indirect	A	3 Low	6
45	Stomata conductance per leaf area	Indirect	A	13 Medium	505
106	Stomata conductance per leaf dry mass	Indirect	A	9 Medium	24
63	Stomata density	Indirect	A	8 Medium	29
1120	Shoot fresh mass per shoot dry mass	Indirect	B	12 Medium	12
3120	Leaf water content per leaf dry mass (not saturated)	Indirect	B	7 Medium	128
2062	Fine root (absorptive) length per absorptive fine root dry mass (specific absorptive fine root length	Indirect	C	3 Low	5

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****		No of observations*****
752	*Plant hydraulic conductance*	*Direct*	*C*	*1*	Low	*1*
1014	*Plant above ground hydraulic conductance*	*Direct*	*C*	*1*	Low	*1*
343	Plant life form (Raunkiaer life form)	Direct	D	36	High	184
NCP	Drought tolerance	Direct	D	61	High	
30	Species tolerance to drought	Direct	D	7	Medium	9
197	Plant functional type (PFT)	Indirect	D	7	Medium	493
	PEST AND DISEASE RESISTANCE					
	Pest and disease resistance					
	Disease Issues	Direct	A	65	High	1
	Insect/Pest Damage	Direct	A	65	High	1
NCP	Animal Damage	Direct	A	18	Medium	
152	Leaf palatability	Indirect	A	8	Medium	10
679	Plant palatability	Indirect	A	4	Low	14
PFAF	Pests repelled - susceptible plants	Direct		11	Medium	
PFAF	Pests repelled by companions - companions	Direct		4	Low	
	Production of secondary compounds					
NCP	Insecticide	Direct	A	16	Medium	
PFAF	Repellent	Direct	A	11	Medium	
NCP	Insect Repellent	Direct	A	7	Medium	
PFAF	Insecticide	Direct	A	2	Low	
NCP	Aromatic Pest Confuser	Direct	A	9	Medium	
PFAF	Scented Plants	Indirect	A	3	Low	
NCP	Fungicide	Direct	B	4	Low	
PFAF	Fungicide	Direct	B	4	Low	

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****	No of observations*****	
NCP	Essential Oil	Indirect	C	12	Medium	
NCP	Chemical Barrier	Direct	C	1	Low	
346	Plant defense mechanisms: chemical	Direct	D	3	Low	3
681	*Plant secondary compounds*	*Indirect*	*D*	*2*	Low	*2*
	Surface barrier to pest penetration					
NCP	Texture	Indirect	A	59	High	
2	Leaf texture (sclerophylly, physical strength, toughness)	Indirect	A	27	Medium	75
1255	Shoot emergences (pubescence, hairs, spines, thorns)	Direct	A	6	Medium	10
	Attracting pest predators					
NCP	Wildlife Food			8	Medium	
NCP	Wildlife Habitat			1	Low	
NCP	Insectory			25	Medium	
NCP	Fruit Type	Indirect		33	High	
NCP	Fruit Time	Indirect		28	Medium	
	Pest host					
NCP	Pest Host	Direct		4	Low	
	WEED CONTROL					
346	Plant defense mechanisms: chemical	Indirect	A	3	Low	3
681	*Plant secondary compounds*	*Indirect*	*A*	*2*	Low	*2*
	ATTRACTING POLLINATORS					
	Floral traits					
NCP	Flower Color	Direct	A	48	High	
207	Flower color	Direct	A	36	High	95
PFAF	Bloom Color	Direct	A	3	Low	
215	Flower UV light reflectance	Direct	A	13	Medium	48
2936	Flower corolla type	Direct	B	12	Medium	13

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****	No of observations*****	
581	Flower conspicuous	Direct	B	3	Low	3
NCP	*Fragrant flowers*	*Direct*		*1*	Low	
	Flowering time					
NCP	Bloom Time	Direct	A	51	High	
PFAF	Main Bloom Time	Direct	A	3	Low	
335	Plant reproductive phenology timing	Direct	A	34	High	363
155	Plant ontogeny: age of maturity (first flowering)	Indirect	A	35	High	187
	Target pollinators					
29	Pollination syndrome	Direct	A	33	High	140
PFAF	*Attracts hummingbirds*	*Direct*	*A*	*1*	Low	
	WEED POTENTIAL					
	Production of volunteers in the following crop					
	Weed Potential	Direct	A	35	High	1
NCP	Invasive	Direct	A	8	Medium	
98	Seed storage behavior	Indirect	B	44	High	140
95	Seed germination rate (germination efficiency)	Indirect	B	32	High	205
1111	Seedbank density	Indirect	B	20	Medium	996
28	Dispersal syndrome	Indirect		42	High	4715
816	Plant morphological adaptations: storage organs	Indirect	C	34	High	116
357	Plant vegetative reproduction: role of clonal growth organ in plant growth	Indirect	C	32	High	126
358	Plant vegetative reproduction: persistence of connection between clonal growth organs	Indirect	C	32	High	124
341	Plant clonal growth form	Indirect	C	31	High	127
344	Plant vegetative regeneration capacity	Indirect	C	25	Medium	52

Trait ID*	Trait name	Direct / Indirect**	Redundancy***	No of species****	No of observations*****
329	Plant vegetative reproduction: clonality of ramets	Indirect	C	15 Medium	21
1206	Plant vegetative reproduction: pattern forming	Indirect	C	9 Medium	14
613	Plant vegetative reproduction: spread rate	Indirect		3 Low	3
819	Plant resprouting capacity	Indirect		8 Medium	14
	Invasive potential				
NCP	Invasive	Direct	A	8 Medium	
242	Species occurrence range: mode of introduction	Indirect	D	20 Medium	22
PFAF	Habitats	Indirect	D	35 High	
PFAF	Range	Indirect	D	35 High	
NCP	Native to North America?	Indirect	D	65 High	
	INTERCROPPING CAPACITIES				
230	Species phyto-sociological group	Direct		22 Medium	62
NCP	Inhibitor	Direct		2 Low	
	INTEGRATION WITH LIVESTOCK				
679	Plant palatability	Direct	A	4 Low	14
NCP	Domestic Animal Forage	Direct	A	8 Medium	
NCP	Animal Toxin	Direct		12 Medium	

Crop traits are ordered by their relative predictive power within each functional group and subgroup.
*Trait IDs indicated for TRY database. NCP and PFAF indicate traits retrieved from Natural Capital Plant Database and Plants for a Future Database, respectively.
**Specify either trait can serve as direct or indirect prediction of particular function.
***Traits marked with the same letter within each functional group may be considered as redundant to increase prediction accuracy.
****Number of species with reported trait value in respective database. Low (1 quartile), Medium (2 and 3 quartile), High (4 quartile)
*****Total number of reported trait value observations for all target species in TRY database.
******Redundant traits reported for less than 3 species and not utilized in polyculture design tool are italicized.

Table S2: Keywords utilized in systemically reviewed publications on integration of spice and aromatic crops with vegetables.

Recommended keyword	Related keywords
Allelopathy (14%)	Weeds (5%), Phytotoxicity (3%), Bioherbicide (2%)
Conservation biological control (3%)	Antifungal activity (8%), Herbicides (8%), Insecticides (8%), Diseases (6%), Pests (6%), Allelochemicals (5%), Alternative control (3%), Predators (3%), Bacteria (3%), Fungi (3%), Pest densities (3%), Pest management (3%), Plant disease (3%), Acaricides (2%), Antifeedant activity (2%), Antimicrobial (2%), Associational resistance (2%), Biocontrol agent (2%), Bioinsecticide (2%), Botanical insecticides (2%), Crop protection (2%), Disease management (2%), Fumigant toxicity (2%), Fumigation effect (2%), Fungitoxicity (2%), Green pesticide (2%), Habitat management (2%), Habitat manipulation (2%), Hatching inhibition rate (2%), Herbivore (2%), Host plants (2%), Host–plant acceptance (2%), Host–plant selection (2%), Insecticidal activity (2%), Integrated pest management (2%), Natural compounds (2%), Natural enemy densities (2%), Natural insecticide (2%), Natural pesticides (2%), Natural substances (2%), Nematicidal activity (2%), Nematicides (2%), Non-chemical methods (2%), Non-prey food (2%), Olfactory behavior (2%), Pathogens (2%), Phytochemicals (2%), Plant-derived antifungals (2%), Repellent plants (2%), Repellent (2%), Selective herbicide (2%), Sustainable weed control (2%), Trap crop (2%)
Intercropping (8%)	Mixed cropping (3%), Companion plant (2%), Companion planting (2%), Crop diversification (2%), Crop rotation (2%), Mixed crops (2%), Polyculture (2%)
Competition (5%)	Interspecific competition (2%), Phytotoxic potential (2%), Root growth inhibition (2%), Seedling growth (2%)
Sustainable agriculture (5%)	Organic farming (5%), Agro-ecosystems (2%), Agroecology (2%), Organic management (2%)