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The Potential of Synergy – Developing a Tool to Design Ecosystems for Sustainable Soil Management

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Abstract
Environmental and economical limitations prompt the search for areas of improvement to reduce the environmental footprint of agriculture, while increasing its resilience and maintaining productivity. We propose a biomimicry approach, where cultivation and productivity are more dependent on intrinsic dynamics than on human/chemical inputs driven by fossil fuels. To specifically target synergetic dynamics and overcome difficulties linked to poor knowledge and hazardous trial-and-error processes, we are developing an informatics tool to design adapted, efficient plant partnerships or clusters. The tool consists of a prediction model that suggests potential win-win plant or other symbiotic relationships, flexible enough to exploit information about local soil/climatic conditions. As the tool gains strength from generated data, it evolves into a simulation model for several-component ecosystem-like systems. In this way, the tool establishes a solid base to support and accelerate applicability of intercropping–type methods, providing realistic expectations about growth and harvest over time, including ecological criteria such as biodiversity. Thus, the tool provides a way out of the deforestation/agriculture dilemma, and opens up possible human soil use during remediation of polluted areas, with significant consequences in many different domains affected by human soil use, including environment, soil stability, health, and climate.

1. Introduction

Past and current improvement strategies for agricultural productivity consisted in finding better ways to manage and save on a whole range of inputs and improvement in the quality of these inputs such as machinery and chemicals. Additionally, the strategy consisted in developing a crop that shows certain useful characteristics (yield, resistance, nutritious content etc.), and on the other side re-creating an environment that can support its growth, through elimination of competitors or pests or through addition of nutrients and water. In recent years, applications of new biotechnology and information technology to agriculture have also been a source of productivity growth for the sector (Fuglie, M., MacDonald, & Ball, 2007). These strategies have been successful in terms of yield increase from 1948 until today, only temporarily interrupted by droughts and energy crisis. While this has proven efficient, some environmental and health concerns and economical limitations trigger the search for other ways of improvement. Adverse influence on the environment includes industrial farming pollution and un-sustainability as energy and water consumption, the emission of harmful substances in large amounts, losses due to erosion.

Indeed, greenhouse gas emissions and water scarcity are widely encountered issues that put agriculture and food industry in general among the biggest contributors to climate change (OXFAM, 2016). Furthermore, while pesticides have shown spectacular effects on sudden pest occurrences or for the protection of harvested goods, it is reasonable to

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be concerned about their effects on the long term. One important concern is their adverse effect on pollinators, in particular wild insects as bees (Goulson, 2013). Knowing the crucial role these insects play for the fertilization of our very own food crops (Garibaldi et al., 2013), the continued use of neonicotinoids is questionable to maintain food production. Indeed, in China, some of the pollination of fruit trees has to be done by hand due to the lack of wild insects and poor knowledge about natural interactions (Partap & Partap, 2002; Partap & Ya, 2012). Furthermore, it is not to demonstrate anymore that a constant race against resistance of pests against pesticides is, for now, keeping up the efficiency of their use, mostly barely delaying the resistance phase (Owens, 2014).

Additionally, small scale farmers especially suffer from vulnerability towards weather variability and markets (UN, 2013). Indeed, while these energy and technology dependencies are often linked to economical dependency or lead to the exclusion of many, the environmental impact is critical and endangers the growth itself on the longer term. This is not even considering the specific role of patented varieties or sterile cultivars in economical dependencies and food sovereignty.

Finally, agriculture based on monoculture stands very often in competition against forests or savannah, or human habitat, forcing to choose among different soil uses as wild life preservation, local food consumption, recreation, habitat, cattle, food exportation, biofuels, etc. These - often difficult - decisions can have dramatic consequences on local and international scale, endangering climatic stability or biodiversity. In this optic, very commonly, economic reasons might prevail for biofuel production for instance, or food need might force the destruction of wild forest, etc. Additionally, social issues as land grabbing are linked directly to the soil use competition.

As a consequence, a conceptual change of the soil management approach is necessary since even the choice meeting the most urgent needs might bear its own destruction. Therefore, many suggestions are drawn, aiming at reducing the environmental footprint of agriculture, increasing its resilience while keeping its productivity. In this manuscript, the choice for a soil management strategy based on synergetic interactions is discussed and a novel informatic tool is proposed.

2. The Strategic Choice for Synergy

The best-known model pictured as alternative is organic farming, which focuses on the environmental impact of pesticides and their impact on human health. While this model shows real effects on the quality of the crops produced, it is often criticized for its lower yield and its lower capacity to resist pests. Furthermore, in its current form it does not offer a real way out from the industrial concept, therefore also depending on parallel energy- and technology chains starting with specific breeding over adapted fertilizers and machineries. Additionally, the issue about the competing space of food crops against forests or energy crops is not addressed.

A bio-inspired approach is proposed in this manuscript: indeed, designing communities working as an ecosystem, instead of single crop systems, bears a huge potential of long term stability and productivity (Landis, 2017), due to a more efficient use of resources as nutrients or water and land surface or light. The underlying principle is to use positive dynamics found in ecosystems and apply them to man-made cultivations. In this way, systems are more likely to resist climatic extreme events and pests offering a two in one function such as food - or other human uses- and ecological functions. This is a reasonable alternative to the monoculture of a given crop, thus resulting in more resilience for its cultivation and a productivity more dependent on its intrinsic dynamics than on human/chemical inputs originating from fossil fuels.

2.1 Productivity - Polyculture bears an important potential for yield increase

The question of the yield gap has been addressed in a recent study on how to close it, using a metadata analysis of current agricultural reports (Ponisio et al., 2015). The largest part of the surface dedicated to agriculture is covered by annuals (FAOSTAT, 2016); in other words, the soil is used only for a fraction of the year. Many crops are also grown as monocultures, with necessary spacing, and leave often a big part of the soil unplanted. There is therefore an unused potential on a given surface. Figure 1 shows the potential of a surface planted with several perennials and annuals. In terms of yield, the advantage or disadvantage of intercropping is usually quantified as a Land Equivalent Ratio (Mead & Willey, 1980), which measures the overall productivity of a given land. For a monoculture, LER is 1, therefore the aim when considering the yield of a poly-culture or intercropping system is to obtain a LER significantly exceeding 1. For more crops on the same surface, there may be less yield per single crop, but in total a higher biomass - this can be calculated with a land equivalent ratio, or LER.

LER = Intercrop1/pure crop1 + intercrop2/ pure crop2 + etc.

This kind of total yield increase has already been experienced and measured in several cases (Gou et al., 2017; Hu et al., 2016).

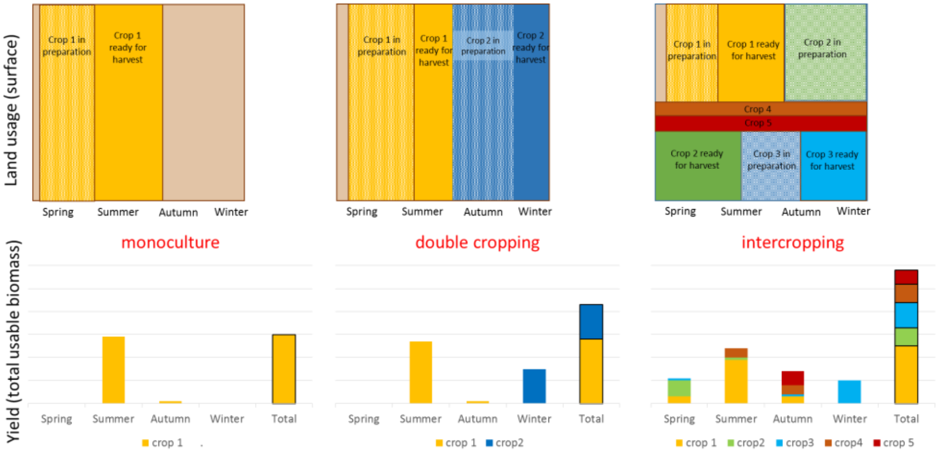

Figure 1: Schematic surface use in different cases of land use (monoculture, double cropping and intercropping including perennials) and total biomass yielded

Nonetheless, mimicking natural ecosystems for agriculture goes beyond the extension of soil use year-round instead of seasonal, or beyond a more efficient way of using light or space.

Studies on beneficial partnerships between crops (Chalk et al., 2014; Franco, King, Masabni, & Volder, 2015; Guo et al., 2014) or adding wild flowers (Balmer et al., 2014), herbs (Tringovska, Yankova, Markova, & Mihov, 2015) or trees (Beaudette et al., 2010) to a crop, are numerous, and show at least an equal yield, if not superior (see Table 1). Plant communities and their partner microorganisms interact in complex, mutualistic beneficial networks. Different ways of combining crops have been developed over time in many parts of the world under the name of intercropping (Sullivan, 1998), agroforestry (Ramachandran Nair, 2014), food forest, or agroecology (Wezel et al., 2009). Many mechanisms are contributing to the generation of these positive effects. The most important of all is a complementarity in nutrient supply and consumption especially through the addition of legumes, through their symbiosis with nitrogen fixing microbes (Rasmussen, Søegaard, Pirhofer-Walzl, & Eriksen, 2012; Scalise et al., 2015), or the control of parasites (Xu, Wang, & Wu, 2015).

Table 1: Examples of yield increases through intercropping

Main crop	Second crop	Companion plants	Effect on growth	References
Legumes		Various		(Chalk et al., 2014)
Peanut	Maize		Increased iron uptake in peanut	(Guo et al., 2014)
Cabbage		Wild flowers	Yield increase	(Balmer et al., 2014)
		Herbs		(Tringovska et al., 2015)
Canola for oil		Trees	Yield identical	(Beaudette et al., 2010)
Cereals		Lucerne		(Harris et al., 2007)
			Yield increase	(Midega et al., 2015)
Wheat	Various		Decrease in pests	(Lopes et al., 2016)
Cassava	Legumes		Decrease in disease incidence	(Uzokwe et al., 2016)
Sunflower	Soybean		Increase in yield (and in water consumption)	(Hamzei & Seyyedi, 2016)
Wheat	Maize		Increase in yield (and in water consumption)	(Miao et al., 2016)
Wheat	Sunflower		Increase in yield	(Miao et al., 2016)
Maize	Bean		Improved yield for maize (soil P-depleted), better nutrient uptake	(Latati et al., 2016)
Rice	Spinach		Increased rice yield Better resistance to disease	(Ning et al., 2017)
Maize	Pea		Yield increase	(Hu et al., 2016)
Maize	Pea, squash = "three Sisters"			(Amador, 1980)
Cotton	Peanut		Cotton yield increase	

2.2 Resilience and stability

Forests existing naturally or semi-naturally everywhere in the world are not watered, host the biggest biodiversity especially in terms of plant and bacterial species, reproduce autonomously and play an essential role in maintaining soil stability, water cycling (Sheil & Murdiyarso, 2009) and cost-effective carbon sequestration (Münnich Vass, 2017). It is also becoming clearer and clearer that neither trees or shrubs alone are the key components for stable flourishing vegetation, instead it is due to the intimate association of a variety of plants with a myriad of microbial soil organisms and animals. In particular, mycorrhiza play an essential role in the nutrient and water uptake of plants, for CO_2 sequestration and for the longevity of trees (Churchland & Grayston, 2014; Terrer, Vicca, Hungate, Phillips, & Prentice, 2016), and constitute an effective communication agent among trees allowing them to react to potential pests. Hence, it makes sense to use the great potential inherent to the forests, in regions where they are native. This implies a shift towards a higher proportion of perennial crops. Currently, a large portion of the agricultural land is covered by meadows and pastures, whereas only less than 5% of the total areas dedicated to agriculture is covered by permanent crops, especially in Europe (FAOSTAT, Jul 14, 2016). The well-established technology and machines around land tillage and harvesting for annual crops underline eventual logistic challenges for a shift to perennials that bias the market in this direction.

2.3 Environmental services through intercropping

The role of permanent vegetation cover through intercropping for other so-called “environmental services” has been demonstrated in several studies (see Table 1). The main focus is on commercially and dietary important crops as maize or rice, which also have a great impact on the environment. These effects include changes in yield, water uptake, soil stability over pest incidence or pollination. While reducing the number of pests might be considered as a side effect and not a strong argument to adopt the alternative method, it is important to build a solid base of knowledge around long-term effects, especially on broadly used crops.

The main factor causing erosion is the presence of temporary or permanent bare soil. Indeed, newly planted crops without vegetation-related conservation practices, when a large portion of the surface is still bare, have erosion rates similar to those of bare soils (Labrière, Locatelli, Laumonier, Freycon, & Bernoux, 2015). Intercropping, on the other hand, sustains soil stability on the longer term (Blanco Sepúlveda & Aguilar Carrillo, 2015; Labrière et al., 2015; Salah, Prasse, & Marschner, 2016). Additionally, carbon storage (Cardinael et al., 2015) or water distribution (Bright et al., 2017), essential for a long-lasting stability and preservation of the soil fertility (Latati et al., 2017; Schwab, Schickhoff, & Fischer, 2015), have been demonstrated. The effect of vegetation in urban areas has also effects on microclimate (Dimoudi & Nikolopoulou, 2003; Duarte, Shinzato, Gusson, & Alves, 2015) and air quality (Pugh, MacKenzie, Whyatt, & Hewitt, 2012). A good understanding of natural interactions also addresses the complex issue about pollination. Indeed, the bare presence or introduction of one species of honey bees or the elimination of toxic insecticides does not guarantee effective pollination (Burkle, Marlin, & Knight, 2013). A combination of compatible plants, seasonal and year-round nutrient and habitat provision for insects and a variety of species are some of the factors essential for an effective fertilization. This is way easier to achieve in a system that is thought from the beginning as a cooperation space among species.

The soil preservation efforts allow the use of other allies of the crops: symbiotic microorganisms. This has been shown through the essential role of fungi in forests (Babikova et al., 2013; Bainard, Klironomos, & Gordon, 2011). Indeed, their role is not only a mutualistic relationship with trees and other perennial plants, providing water and mineral oligo elements in change of sugars, but is also allowing communication within a population of trees or between different trees; permitting, for example, to adapt to invasion of parasites.

In other words, by promoting intercropping, and optimizing even the use of companion plants, many environmental services would be used in their full potential.

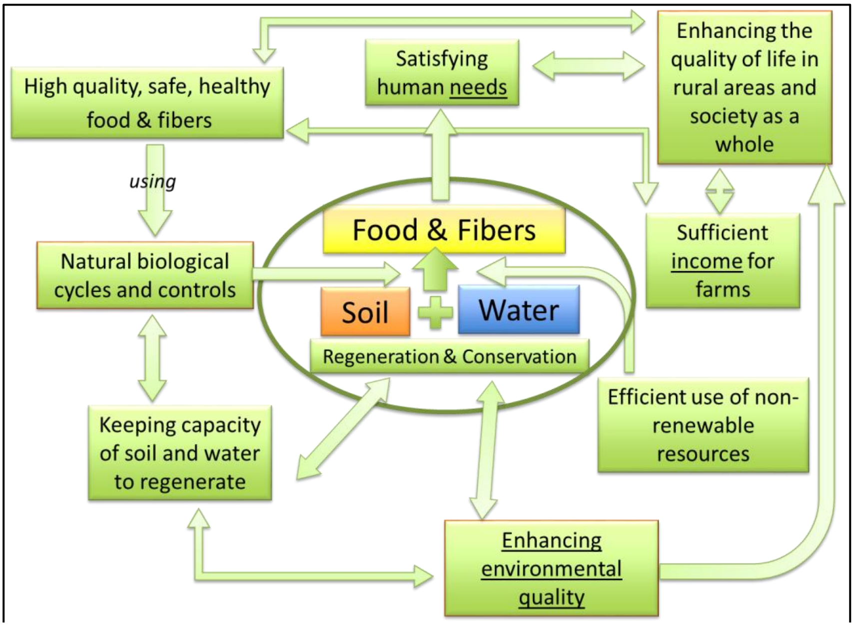

Figure 2: Conceiving soil management as an functioning ecosystems implies many positive consequences on human and environment

3. The Need for a Practical Tool

Despite many advantages for an ecosystem-inspired system, a well-established production chain organized on monoculture, the time consumption of new trials and failures, with the risk of harvest losses and its accompanying human consequences put a brake to the application of plant grouping into agricultural methods. Additionally, the results obtained through small scale experiments are little known outside of the circle of scientific researchers or experimental farmers, limited to very local conditions or poorly documented, which lowers their reproducibility and applicability. Even if the outcomes are known and well documented, their replicability and reproducibility on other sites is hazardous because the plants and methods were developed for one specific site, and that might be one of the reasons why these studies do not receive the right credit. The resilience of ecosystems has been studied, nevertheless there is also a need for measure of the threshold diversity needed to provide this ecological service (Sasaki, Furukawa, Iwasaki, Seto, & Mori, 2015). Finally, the information about partnerships for remediation plants is extremely poor, probably due to the recent development of this category of cultivation.

Another main limitation to the spreading of plant organized in partnerships is the lack of means to estimate the harvest gain or sustainability over time gain. Currently, there is no realistic method or way to quantify yield and profit from such mixed system, which makes it difficult to convince potentially interested investors or farmers to give such methods a try and start investigating.

Eventually, natural ecosystems get established by themselves when given enough time and freedom. The output might however not always be of use for humans, and might undergo several phases over long periods of time before it gets established. On the other hand, if a community is built merely selecting desired crops on a random base, it might not exhibit the functioning properties of an ecosystem, including some essential ecological functions that might be missing or overlooked. The community will therefore not be able to develop its potential. A recent study by Zawadzka et al. shows how important it is to quantitate the ecological gain through this approach (Zawadzka, Corstanje, Fookes, Nichols, & Harris, 2017).

3.1 The approach suggested

In order to provide a good base to develop serious alternatives to current models, there is a need to overcome limitations, offering tools for the development and application of acceptable alternatives, in particular the choice of crop partnerships.

A good point to begin with is to fill up the gap between on one hand the current models– characterized by monoculture and high human input – and on the other hand a system based on polyculture, high resilience and lower ecological footprint, through the development of an informatic tool capable of designing adapted, efficient partnerships or clusters.

The informatic approach is articulated in 4 points:

1) collection of current knowledge in a reliable and organized way making it available to a large number of users,

The tool proposed consists of an interactive flora and microorganism database. It will contain a catalogue of plant categories and properties, their ecological strength and partners, but will also provide a list of possible plant or microorganism partnerships adapted to the conditions required. It should be able to answer questions about present knowledge on botanic and practices, organize the knowledge on soil/plant compatibilities as well as known symbiotic partners.

2) a predictive algorithm which suggests potential win-win plant- or other symbiotic partnerships, as adapted as possible to the given soil/climatic conditions, especially where no knowledge is available - A knowledge-gap filler

*The tool is designed to provide enough reliable information in order to establish a more ecosystem-based way to conceive cultivation and vegetation, by growing more than one species at the time, as a system rather than a single isolated species. This association is named here a "**cluster**".*

The user will choose requirements from soil, climate, plant partners or other known local specificities to filter a choice of plant clusters with the highest probability of growth under the given criteria and present knowledge. The ranking of these suggestions will be based on a score given based on the match with the *given conditions on one side, and on the availability and reliability of data on the other side.*

3) a self-improving tool as new information is acquired: dynamic acquisition of data while experiments or applications are run.

It is meant to become a growing interactive tool. The more knowledge is added, the more solid the suggestions will be. Thus, it can be extended to an open source database, where users can use their experiments as new input to improve further use. In this way, introducing a quality standard for input data, users could also become contributors to a more complex and useful version of this tool, towards simulation and prediction. The functioning tool will therefore accelerate the collection of a new type of data, the methodology and results of harvest and sustainability.

4) a predictive model for harvest and system resilience against climatic or pest events.

Using data that include dynamics or a time line, as soil percent coverage, biomass produced, harvest, resistance and recovery against hazards (pests, extreme or unexpected weather/climatic events), ecological impact, interaction with other organisms (insects, mammals, etc.). This tool will be able to provide, at a later development stage, an estimation of the gains (compared with a monoculture), as well as a time scale, allowing a real simulation for several-component ecosystem-like systems over time. Eventually, it will be really able to establish a solid base to support alternative plant growth models, providing realistic expectations about growth and harvest over time, including ecological criteria as biodiversity.

3.2 Tool input and basic construction of the data set

The first requirement is of a minimum of 350 plant species with sufficient information on their properties, partnerships and usefulness. At least 4 families should have over 10 represented species and at least 10 families of plants should be present. Also, a total of 30 bacterial and fungal partners should be included. The next step includes all plants used by humans for food, feeding purposes, medicine, remediation, fiber and timber, and their symbiotic partners.

Table 2: Basic construction of the dataset.

Essential for a good functioning tool	partial data set sufficient for a start	Good improvement if present	Optional extensions
Plants (start with human use related ones), trivial name in English	**Known relationships*** between plants Positive synergy Antagonism	Data on more than one to one interaction (groups of 3 or more, small ecosystems)	Human uses (remediation, medicinal, food, etc) → *filter by use or as a convincing point to plant that otherwise unknown plant*
Bacteria & fungi (start with agri-ecological relevant ones)	Plants-microorganisms interactions (symbiosis)		Interaction with other organisms: pollinators, pests, wildlife → *use for biocontrol or wildlife restoration*
Latin binomial nomenclature	**Properties** $ **(ecological, tolerances, etc.)** N fixer pioneer accumulator Root type Salt	Growth type: tree, vine, shrub, soil cover	Other names for organisms, translation in different languages
	Growth requirements # nutrients water	Methods for an adaptation to climate challenges, drought, etc.	Handling instructions: spacing, seasons, varieties, maintenance, time frame → *make it usable in practice*

	climate Soil type light		Growth data for plants, especially for perennials (time to reach maturity, sizes for trees, time till significant harvest, when need replacement, maintenance Links to local seed banks and providers, with varieties
Botanical/scientific classification: reign, genus, family	Reliability of data (score)		

Notes:
*relationships, in particular among plants, are the key point and the bottleneck of this data collection. Obviously, the output can only be good if the input is good enough, so a minimum of knowledge is necessary in order to provide an input for a program to estimate good matches.
$ Main properties: Nitrogen fixation, pioneer plant, (metal) accumulator plant, root type (tap root, flat rooter, etc.), salt tolerance/intolerance, juglone tolerance/intolerance are mostly yes/no data. Other properties ought to be added as text or multiple choices.
#Optimal or tolerable growth conditions as known. Nutrient requirements ("heavy feeder", specific element needs), water (dry, wet), climate zones, soil types and properties (clay, sandy, rich in organic matter, heavy, poor, rocky, dense, etc.), light conditions (shadow tolerant or lover, half shadow, full sun, etc.). Others (as spacing, or special growth conditions) added as text or notes.

3.3 Relevant topics

The main topics that are to be browsed for can be listed under the following **key words**:
intercropping, poly-culture, traditional agricultural practices, symbiosis, symbiotic edible mushrooms, N-fixers, rhizobacteria, endophytic bacteria, mycorrhiza, hyperaccumulator, bioremediation, companion planting, crop rotation, stable ecosystem, permaculture, pioneer plants, biomimicry, edible forest, agroforestry, double cropping, agroecology, biomimicry, life cycle for trees, energy crops, fiber crops, agriculture, traditional agriculture
Of note, the information will be selected and chosen based on different criteria and sources, as summed up in table 3.

3.4 Data acquisition

3.4.1 Basic settings

There are many available programs allowing to collect data in a systematic way and permitting a professional data organization (PostgreSQL, Access, mySQL, etc.). The important factors for the choice of the database are the compatibility with further data management programs, the user-friendliness and the potential for usability in further programming and simulations. Several plant catalogues or programs to plan a garden setting already exist and provide valuable and essential information. The novel concept presented in this manuscript goes beyond that. Indeed, the approached here presented proposes to find and fill out knowledge gaps linking them to predictive and simulation programs.
The dataset is to be kept up-to-date in order to keep the tool reliable on one hand and to improve its usefulness on the other hand. The reliability of the information should also

be regularly evaluated based on new acquisitions.

3.4.2 Source of the data

Highly reliable:

- Established basic biology knowledge (botanical classification, symbiosis, juglone tolerance, etc.)
- scientific peer-reviewed articles from academic universities, environmental and agricultural (governmental) institutions (USDA, EU), United Nations (FAO) NGOs

Input that requires curation: (grey data)

- main stream journals which report scientific discoveries
- non-academic experimental groups for gardening, permaculture, and similar
- historical facts, traditional cultures and practices

Table 3: Input data and sources

Type of data		Source
Criteria for plant choice	Plants used in agriculture for food production, feed, fiber, energy production (at first focus on temperate/ Mediterranean climate zones)	Any literature on commercially important food/feed/etc. plants.
	Plants commonly present in fields, cities, with relevance for pollinators, medicine.	
	plants used for bioremediation	
	Paying attention to local vs invasive plants is also important	
Botanical classification	Focus on binomial name (species+ genus), variety if relevant and family. Other classification only if relevant	Found in many established literature sources since they are well known plants, botanical literature
General properties common to a family	Properties common to a whole botanical family	Botanical literature
Present traditional or alternative cultures and practices		International and national agricultural institutes, farmers' organizations
Historical point of view		Museum data open to the public, historical books
Fungi / Mycorrhiza	Literature about edible fungi and their tree partners	Established literature and new releases in scientific publications
Nitrogen fixation	Known plant and microbial partners	Established literature and new releases in scientific publications
Plant partnerships		Scientific publications, experimental gardening and established permaculture compilation (latter ones with less reliability score)

4. Conclusion - Usefulness

An ecosystem-based soil management intends to include several levels of the biological organization, from the organisms, populations and community to the ecosystem. It enlarges the field of possibilities regarding erosion control, nutrient cycling, mutualisms and the auto-stabilization of the system.

Here, the proposed tool aims to make a better use of already existing data, encouraging people in the field to save years of hazardous experiments and giving a chance to improve growth or resilience of cultivations, especially where more research is required, as for instance on remediation plants or challenging soil conditions.

Furthermore, as a universal and openly available predictive model for known and potential win-win partnerships of plant clusters, flexible enough to exploit information about local conditions, it will accelerate the applicability of intercropping–type methods. Indeed, the build-in algorithm can find adapted plant and microbial partners to crops and can additionally consider and include additional functions of crops, as soil fertility increase, erosion control, pollinator conservation, soil remediation, which give a soil even more short- and long term ecological value and impact as a reduced greenhouse gas emission level from food production. Using this tool, the user chooses requirements from soil, climate, plant partners or other known local specificities to filter a choice of plant clusters with the highest probability of growth under given inclusion/exclusion criteria and cutting-edge knowledge, considering that the tool improves the more it gets used.

As open-source embedded in a human network, this tool can offer a series of advantages. It can ease a conversion to a general agroforestry model, partly resolving the deforestation/agriculture dilemma; it can give an alternative to deforestation through coppicing and inter-cultures to sustain the soil in the main time, having significant consequences on soil stability, climate and pollination; it can give useful alternative and parallel plant uses on polluted areas, motivating the start of phytoremediation projects; it can reduce the impact of the dependency on one species and empowers the local initiatives and cultures.

Overall, by giving this solid documentation and applicability base to an alternative approach to soil use, it is reasonable to expect several positive outcomes in many different domains affected by human soil use, as environment, human health, and climate.

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