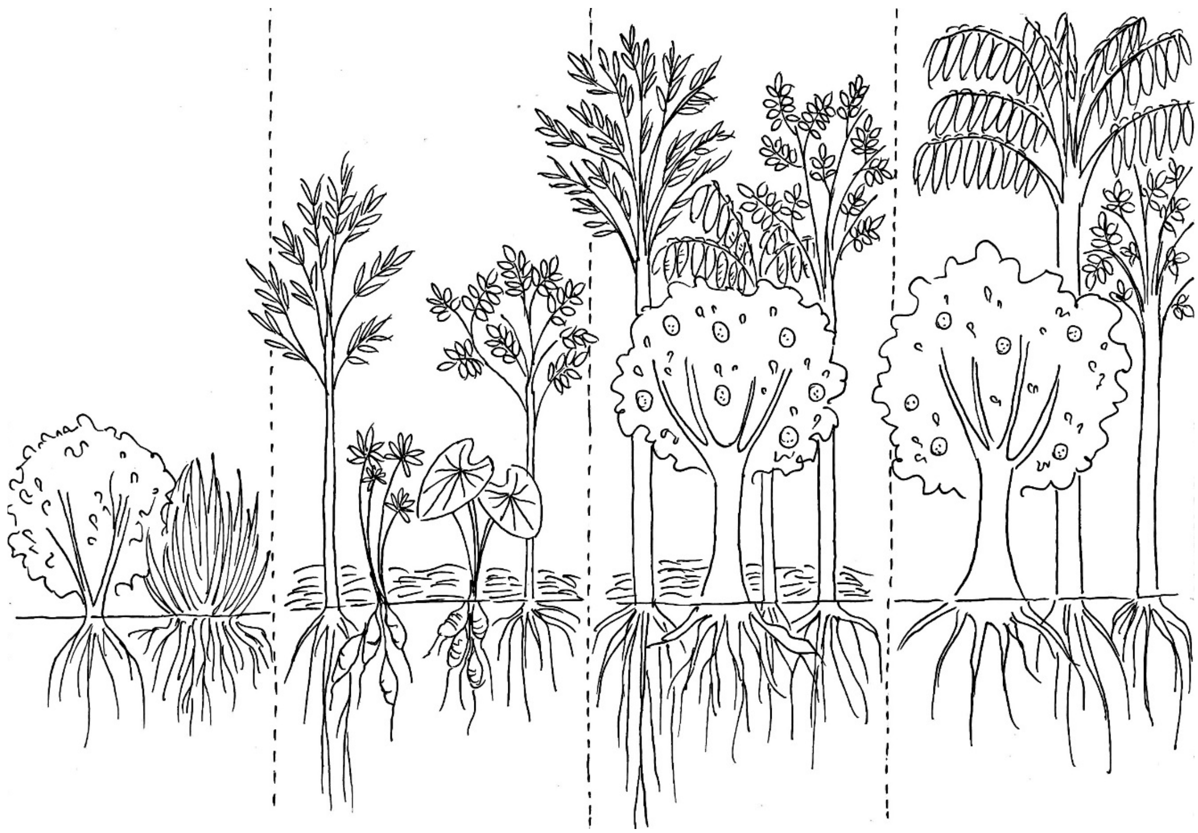
From the Atlantic forest to the Mediterranean shrub land: a Farm Performance Assessment and a Functional Design Framework for Large-Scale Successional Agroforestry Systems (SAFS)

MSc Thesis in Organic Agriculture



Student: Donatella Gasparro

5th November, 2019

Farming Systems Ecology & Farm Technology Group

Droevendaalsesteeg 1 – 6708 PB Wageningen - The Netherlands

WAGENINGEN UNIVERSITY & RESEARCH

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Student name: Donatella Gasparro

Registration number: 950406250040

Course code: FSE-80436

Date: 5th November, 2019

Supervisors: Carl Timler (Farming Systems Ecology) and Arni Janssen (Farm Technology Group)

Professor/Examiner: Rogier Schulte

CONTENTS

ABSTRACT

In the context of human-induced climate change and the growing global population, agriculture and the food system are in the spotlight. A radical shift towards diversified and regenerative farming systems, imitating the functioning of natural ecosystems, is urgently needed at all scales. This study aims to: 1. assess the environmental and economic performance of a large-scale Successional Agroforestry System (SAFS) for Tahiti lime (*Citrus x latifolia*) in Brazil; 2. compare the economic performance with the case study SAFS with an organic and a conventional citrus farm performance; 2. design a Functional Design Framework for SAFS in different biophysical contexts, based on a function analysis of the case study farm. The FarmDESIGN modelling tool was used to assess the farms' performance with environmental and economic indicators. Methods from Reflexive Interactive Design (RIO) for bio-systems design were used for the function analysis and the framework design.

The case study large-scale SAFS perform well under both the environmental and economic point of view, with a net addition of 294 kg ha^{-1} $year^{-1}$ of soil organic matter, 0.17 Mg ha^{-1} $year^{-1}$ increase in soil organic carbon, high nutrient cycling rate and high Shannon and Margalef indices. Operating profit was found to be higher in the SAFS (51,000 R$ ha^{-1} $year^{-1}$) than in both the conventional (32,000 R$ ha^{-1} $year^{-1}$) and organic citrus farms (45,000 R$ ha^{-1} $year^{-1}$). Despite labour requirements being the highest for SAFS, the sales of by-crops such as timber were found to over-compensate for the higher costs and the fruits yield-gap. This study demonstrates that large-scale complex agro-ecosystems such as SAFS not only provide ecosystem services but are also economically viable, thus offering a replicable alternative to large scale industrial agriculture.

A set of thirteen functions and relative sub-functions that need to be fulfilled in SAFS across different environments were identified. Based on these, a Functional Design Framework for replication of SAFS was created. Plant traits associated to the performance of these functions were selected. The Functional Design Framework includes the functions in morphological charts of solutions, and strata and successional stage matrices, which can be used in an iterative design process. The framework was tested for a theoretical SAFS design for the Mediterranean climate, which demonstrated the framework's validity and usefulness across different contexts.

KEYWORDS

Agroforestry; Successional Agroforestry; FarmDESIGN; Reflexive Interactive Design; function analysis; Functional design framework.

1. INTRODUCTION

1.1. The global context

In the context of human-induced climate change (IPCC, 2018), with global population expected to grow to 9.8 billion people by 2050 (United Nations, 2017), agriculture and the global food system are in the spotlight, with the prevailing discourse arguing that production should rise by 70% by 2050 in order to meet the global food demand (Tilman et al. 2011). Nonetheless, current food production is enough to fulfil the needs of humankind (WHO, 2013), but 821 million people are undernourished (FAO, 2018) and one third of the food produced globally is lost (FAO, 2011). Moreover, the high yields of today's industrialised and standardised farming and food systems often come at the cost of environment and society, with agriculture contributing to the exceeding of planetary boundaries such as biosphere integrity, biogeochemical flows and land-system change (Campbell et al. 2017).

A radical shift towards diversified agro-ecological food systems is urgently needed: incremental changes and mere tweaking of practices cannot provide long term solutions for the problems industrial agriculture has generated (IPES FOOD, 2016). A new model based on diversification of farms and landscapes is necessary (*ibid.*), aiming at ecological intensification through the use of natural functions of ecosystems (Tittonell et al., 2016). We are urged to not only stop doing harm, but to make net positive impact on the environment, designing radically different agro-ecosystems that go beyond sustainability and aim at regeneration (Figure 1) (Reed, 2007).

The observation and mimicry of nature can provide tools for designing regenerative agro-ecosystems (Malèzieux, 2011), with the goal of increasing soil quality and agro-biodiversity, profitably (Rodale, 1983). Although there is no consensus on a definition of regenerative farming in the scientific community, practices such as no tillage, holistic grazing and agroforestry are generally grouped under its umbrella. Agroforestry (AF), defined as the practice of integrating trees or shrubs with crops and/or livestock (AGFORWARD, 2015), is one of the ways we can ecologically intensify agro-ecosystems, creating environmental, economic and social benefits, for instance combining high yield and high biodiversity on farm (Prabhu et al., 2015). AF systems can serve as carbon sinks and biodiversity pools that can play a relevant role in the mitigation of and adaptation to climate change, especially in the tropics (Jacobi et al. 2014).

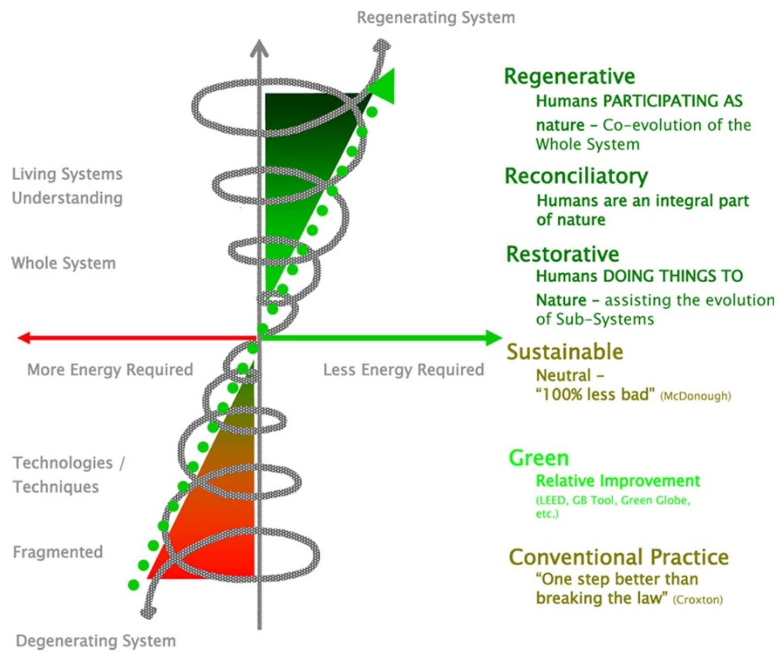

Figure 1 – The shift from a degenerating system to a Regenerative one, beyond sustainable. (Reed, 2007)

1.1. The role of large-scale farms

Redesign towards diversification must happen at the landscape level to have significant impact (Tittonell et al., 2016; IPES Food, 2016). Not only small-holders and subsistence farms are called for action, but also large-scale industrial farms, as diversification is possible and desirable at all scales (Altieri & Rosset, 1996; IPES Food, 2016). Large-scale industrial farms, being responsible for most agricultural related problems, have also the greatest room for improvement and the most urgent need to re-evaluate their production systems (IPES Food, 2016; WWF, 2016). Although some exponents of alternative agricultural philosophies regard truly sustainable farming as possible only on small-scale, it is not realistic to ignore the growing urban population and the necessity to produce large quantities of food to deliver to cities (Rigby & Cáceres, 2001).

Complex agro-ecosystems such as Successional Agroforestry Systems (SAFS) are usually more knowledge and labour intensive (Mercer, 2004), which makes them more easily applicable on small and medium scale farms, where labour is often provided by family members (Arthi et al., 2018). Another limiting factor for large-scale implementation of complex agro-ecosystems can be seen in the current mass commodity market lock-in of industrial agriculture, in which great amounts of one uniform product are produced, distributed and retailed. In this scenario, allocating multiple products on the market requires re-thinking not only production strategies but also business strategies, suggesting the need of not only redesigning farming systems but also food supply chains and food systems entirely (IPES Food, 2016). It is not surprising that adoption of SAFS on large-scale farms is still infrequent and at an experimental phase, and has not received much research attention yet. Nonetheless, large-scale farms have potentially more resources to invest in the initial implementation phases of these agro-ecosystems. Analysing the farm-level performance and the design of existing large-scale examples is a key step towards optimization and replication of successful practices across different environments.

1.2. Successional Agroforestry Systems (SAFS)

Agroforestry practices vary greatly in complexity and scale (Nair, 1985). Successional Agroforestry Systems (SAFS) are complex agro-silvicultural systems that aim at imitating the successional dynamics and the vertical stratification of native forest ecosystems. Succession is defined as the progressive alternation in structure and species composition of the vegetation (Grime, 1979), while stratification, although debated (Parker & Brown, 2000), is usually referred to as the vertical division of vegetation layers (or strata), which are often reduced, for simplicity, to four: emergent, canopy, sub-canopy and understory. In SAFS, the structure of the natural occurring forest is mimicked with both productive and 'support' species, resulting in a dynamic plant community which is both productive and beneficial to the (agro)ecosystem regeneration (Jacobi et al. 2014). Natural processes are accelerated through frequent pruning of fast-growing plant species with the aim of keeping the system 'young', avoiding the plants' senescence phase with the 'rejuvenation' or removal of those at the end of their life cycle (Schulz et al. 1994). The abundant biomass resulting from pruning is chopped and accumulated on the fields as mulch, in order to cover the soil and improve soil quality, fostering nutrient cycling and consequently reducing external inputs (*ibid.*). The effectiveness of SAFS in being productive while providing a wide range of ecosystem services has already been shown in several studies (Jacobi et al., 2014; Armengot et al., 2016; Schneider et al., 2017; Schneidewind et al., 2018). Many of the SAFS draw from traditional techniques, while others are based on recent cultivation methods and philosophies mostly deriving from the work of Ernst Götsch, who founded Syntropic agriculture in the state of Bahia, Brazil (Schulz et al., 1994).

1.3. Problem description: from structure to function

Large-scale SAFS have yet to be widely studied and spread amongst a large number of farmers. Given the urgency to have large-scale impact, it is a key step to analyse the performance of existing large-scale SAFS examples in order to assess their performance, their potential and their limitations and to optimise their design.

Moreover, there is a lack of distinct design tools that facilitate the replication of these complex systems, and, being plant species, and the knowledge to these related, strongly context dependent, it is difficult to apply existing SAFS designs in different biophysical environments. For this reason, abstracting the 'structure', here intended as the different elements and their relations within the system (in this case, the plant species), to their 'function' (Figure 2) (van den Kroonenberg, 2002), that is the role that these elements fulfil in the system, can provide a starting point for laying the basis of a design framework valid across different climates and biophysical conditions, assuming that different plants with similar functional traits can perform similar functions in different environments.

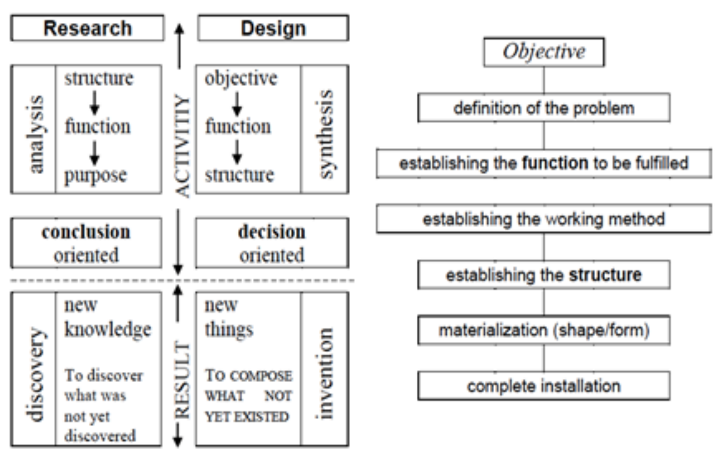

Figure 2 – From Structure to Functions (Analysis) and vice-versa (Design) (van den Kroonenberg, 2002)

1.4. Background information and definitions

Functions

Ecologists have long shown interest in the functions and roles plants play in natural ecosystems, but this knowledge has not been widely applied in agro-ecosystems yet. Nonetheless, the concept of "nature mimicry" to design agroecosystems is not new. This approach is based on the assumption that the structure and functioning of natural ecosystems can serve as model for the design of agricultural systems (Malèzieux, 2011). Some authors have already proposed frameworks for designing farming systems based on nature examples. Already Hobbs and Morton (1999) identified a series of steps including the identification of functions and of the key species that can fulfil them in natural ecosystems. Malèzieux (2011) proposed a three-step framework, which starts from the observation of the ecosystem in order to identify the functions and the functional characteristics to be mimicked. Knowledge of the local natural ecosystem is required for this step, and local farmers can often be a great source of agro-ecological knowledge based on the observation of nature (*ibid.*). Nonetheless, none of the mentioned design frameworks identifies the functions useful for design.

Jax (2005) identifies four different meanings for "function" within the domain of ecology and environmental sciences: 1. functions as processes; 2. the functioning of a whole system; 3. functions as roles of elements within the system; 4. functions (of the whole system) as services to humans (ecosystem services). In the Agroforestry literature, 'functions' are found as a varied set of 'services and products', 'uses', 'roles', 'outputs' (Dawson et al., 2014; Fernandez and Nair, 1986; Nair, 1987). Jax (2005) also argues that "In contrast to parts of an organism, a particular species has no clearly defined role within an ecosystem"; "The" one and only role of a species does not exist. Roles are strongly context-dependent." Nonetheless, Jax concludes that it is scientifically sound to talk about functions of species within a system, as long as we acknowledge that "functions and ecosystems cannot as such be found or identified in nature, but to a high degree depend on defining the specific systems and reference states which are to be investigated."

This study adopts the definition of the bio-systems design vocabulary: a function is what needs to be performed by the system (and the system's elements) to reach the system's objectives. In a technological installation, for instance, a function is "the transformation which has to take place in that installation to achieve the objective. The function can be considered the core of the design. The crucial question in assessing the function is what has to be done to achieve the desired results." (van den Kroonenberg, 2002).

Functional traits

Functional traits are "morphological, anatomical, physiological or phenological features measurable at the individual level" (Violle et al., 2007) and, regarding the interaction with the environment, can be divided into effect traits and response traits. Effect traits reflect the effects of a plant on the environmental conditions; response traits are such when their attributes vary in response to changes in the environmental conditions (Violle et al., 2007). Here we focus on effect traits, those influencing and changing the environment. Response traits are instead, design wise, dependant on the plant requirements in a specific ecological context.

1.5. Objectives & Research questions

The objectives of this study are:

- to assess the environmental and economic performance of a large-scale SAFS example from Brazil;
- to compare the economic performance of the case study SAFS with one conventional and one organic farm of the same area;
- to compare the performance of two different SAFS designs of the case study farm;
- to design a novel Functional Design Framework valid across different contexts, based on a function analysis of the components of the case study SAFS.

Research questions

What is the environmental and economic performance of the case study large-scale SAFS?

- How do large-scale SAFS perform in SOM balance, Nutrient Cycling, SOC sequestration, Labour requirement, Operating profit, and Crop sales margin?
- What is the difference in economic performance between the citrus large-scale SAFS and an organic and a conventional monoculture citrus orchard from the same study area, in regard to operating profit, crop margin and labour requirement?
- What is the difference in agronomic, environmental and economic performance between two different large-scale SAFS designs? What is the difference linked to?

Which functions do the elements in the case study SAFS system perform?

- What are the large-scale SAFS system's objectives?
- What functions are needed in the system to fulfil the objectives?
- What functions are fulfilled by plants and what plant traits are associated to the performance of these functions?
- How can these functions be used as a design tool in other biophysical contexts?

2. MATERIALS & METHODS

2.1. Data collection: the case study area

The Study Area

The case study farms are located in the mesoregions of Piracicaba and Araraquara in São Paulo state, Brazil. This area, close to the Tropic of Capricorn, is characterized by a humid subtropical climate according to the Koppen's climate classification (Alcarde Alvares et al., 2014). The Cerrado biome dominates the central part of São Paulo state, and the Atlantic Forest biome prevails along the coast. The latter is one of the world's biggest biodiversity hotspots (Ribeiro et al. 2011). São Paulo state's annual rainfall ranges between 1,200 and 1,600 mm (Alves et al. 2011) with distribution concentrated in summer (November to March).

Figure 3 – Itirapina, São Paulo, Brazil. Case Study farm location (Global Forest Watch, Google Earth engine)

From the agricultural perspective, São Paulo state is the biggest producer of sugarcane and oranges worldwide and has the most developed agro-industrial system of Brazil. Besides oranges, other *Citrus* species are grown, including lemons and limes. The study area was one of the first ones in Brazil to be affected by the Huanglongbing (HLB) disease, also known as Greening, considered the most important and destructive of all *Citrus* diseases. HLB was first found in São Paulo state in 2004. It is caused by *Candidatus Liberibacter sp.* and transmitted by the vector *Diaphorina citri* (Texeira et al., 2005). There is no cure for the infected trees, and, between 2004 and 2007 alone, more than half million trees were uprooted in Brazil, plus an estimated 400 thousand unofficially eliminated by growers (Gottwald et al. 2007). In 2018, approximately 18% of trees in the commercial area of São Paulo and Minas Gerais were found infected by HLB (USDA, 2018).

The Case Study farm: Rizoma's SAFS at Fazenda da Toca and the two comparison farms

Rizoma is a Brazilian company researching, implementing and producing with regenerative agricultural practices. It has the ambition to regenerate 1 million hectares of land by 2030 through agroforestry systems, silvo-pastoral systems and organic annual crops. Rizoma is one of the 'Lighthouse farms' in the Lighthouse farms network coordinated by the Farming Systems Ecology group at Wageningen University & Research. The project aims at creating a worldwide network of exemplary farms that embody what can be achieved in terms of sustainable food production within their bio-physical and socio-economic contexts. Rizoma operates on 300 of the 2300 hectares of Fazenda da Toca, an organic farm located in Itirapina, part of the mesoregion of Piracicaba. When the study was carried out, 36 ha, mainly of sandy Oxisol, were planted with organic Successional Agroforestry Systems, eight of which were initially designed and implemented in collaboration with Ernst Götsch as a way to cope with HLB disease. Despite the improvements after the implementation of SAFS, most *Citrus spp.* trees on farm were eradicated before the end of 2018, due to the high infection rates. New SAFS were planted, starting in 2016, with more resistant varieties of fruit trees such as Tahiti lime (*Citrus x latifolia*) grafted on Fly Dragon rootstock (*Poncirus trifoliata var. monstruosa*). The company's vision is to reach 400 ha of SAFS, so all designs aim to be large-scale compatible. This study focusses on two fields, implemented in 2016 and 2018, with two different designs (Table 1), for a total of 27 hectares. Detailed illustrations of the two analysed SAFS designs and can be found in Figures 5 & 6 (Field 5), and Figures 7 & 8 (Field 8).

Figure 4 – Banana pruning in the SAFS on field 5 at Fazenda da Toca.

In the SAFS of the case study farm, early successional stages see a first year with a grass (*P. Maxicum* or *Brachiaria spp.*) combined with a pulse (*C. Cajan or Crotalaria sp.)* for the bulk production of plant material to accumulate as mulch on the planned tree lines, followed by the planting or seeding of all other species that will dominate in time. Tuber crops such as cassava (*Manihot esculenta*) and yam (*Dioscorea sp.*) follow, while banana plants (*Musa* sp.) and eucalyptus (*E. Urograndis*) start producing great amounts of biomass and shade lower strata. Banana is cut back every two months manually with a machete, and the chopped plant material is accumulated on the lines. Eucalyptus is pruned twice a year after the first year and the wood is chopped and accumulated on the tree lines.

Tahiti lime *(Citrus x latifolia)* starts producing at the 4th or 5th year and occupies a sub-canopy layer in the vertical stratification, thus requiring a light shade, thought to be important in HLB control and provided by canopy and emergent trees. Timber trees such as red cedar (*Toona ciliata*) and African mahogany (*Khaya ivorensis)* will be the last dominant species of the system, harvested at the end of the cycle (approximately 20 years old). In the design referred to as field 8, banana plants are not present, but leguminous trees (*Inga laurina*, *Inga vera, Erythrina fusca, Erythrina poepegiana, Gliricidia sepium* and *Schyzolobium parahyba*) are planted and used as well as green manure when pruned. In both designs, tree lines are alternated with grass strips (*Panicum maxicum*) that are mowed 5-6 times per year. The resulting plant material is accumulated on the tree lines as green manure/mulch.

Designs overview Fazenda da Toca - Fields 5 & 8			
		Field 5	**Field 8**
Area	ha	6,36	21,05
Year of implementation		2016	2018
Spacing between lines	m	7	5
Species No./ha	*C. x latifolia*	588	909
	P. maximum	80% of area	80% of area
	Musa sp.	588	0
	E. urograndis	294	606
	G. sepium	0	30
	Erythrina spp.	0	30
	Inga spp.	0	30
	S. parahyba	0	15
	K. ivorensis	294	150
	T. ciliata	0	150

Table 1 - Design overview of studied SAFS at Fazenda da Toca, including spacing and approximate plant numbers.

The SAFS are fertilized with chicken manure and micronutrients, and biocontrol agents such as *Isaria fumosorosea* and *Beauveria bassiana* are periodically sprayed in the SAFS to control the vector of HLB.

Fazenda da Toca's SAFS performance was compared with data gathered from two other Tahiti lime farms located in Itápolis. The case study conventional farm grows Tahiti lime (clone "Quebra-galho") in monoculture on 58 hectares, on a loam red Latosol. The citrus orchard spacing is 6 x 7 m with 560 trees ha^{-1}. Weeds are managed with herbicides, the soil is left bare and fertilization consists mainly in chemical NPK and micronutrients. The second comparison farm is a small 2 ha organic farm growing Tahiti lime in monoculture on a clayey Oxisol, with a tree density of 476 plants ha^{-1} spaced in 3 x 7 m. Weeds are managed with mowing between the tree lines. The orchard is fertilized with organic fertilizers; natural enemies and plant oils are used for pest control. The farm also includes a greenhouse for vegetables production in winter and a papaya field, which have not been modelled.

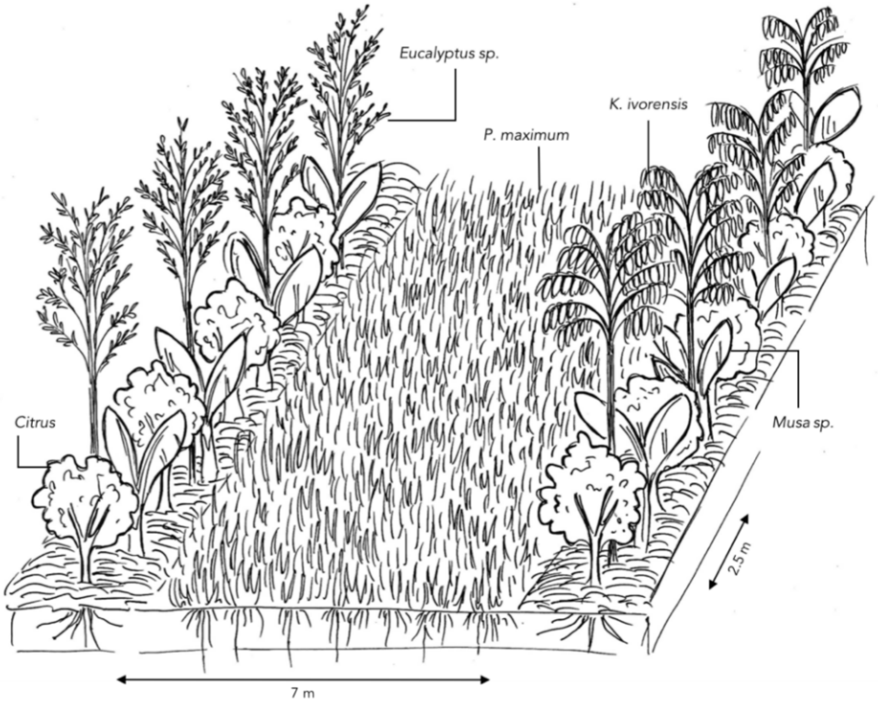

Figure 5 – Fazenda da Toca's SAFS on field 5, isometric. Spacing and plant distribution. Eucalyptus sp. and Khaya sp. are planted on alternated rows. Own elaboration.

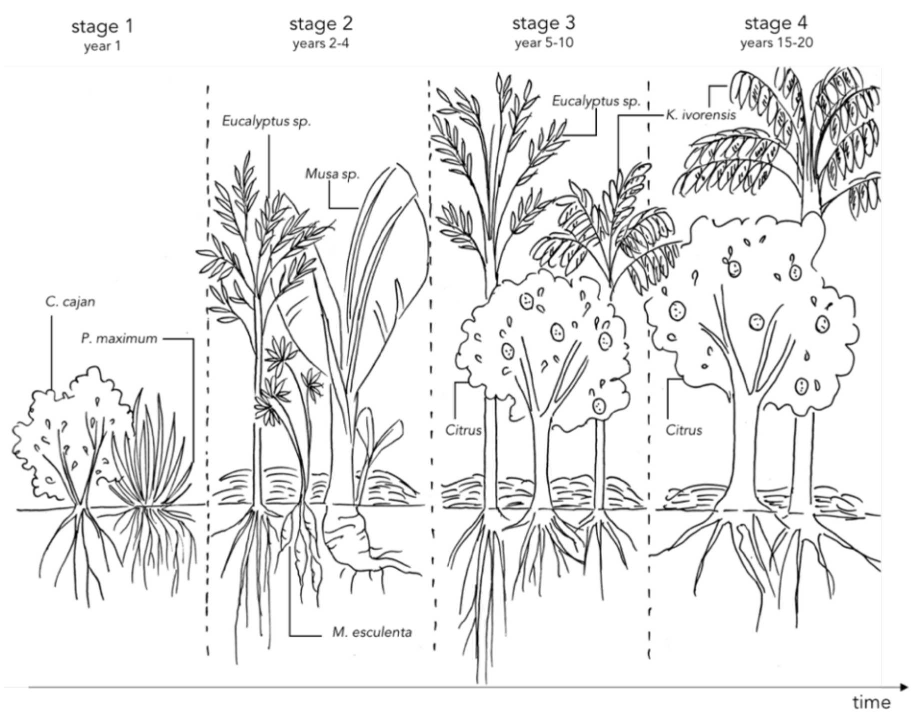

Figure 6 - Fazenda da Toca's SAFS on field 5, section. Successional stages impression on the tree line. Own elaboration.

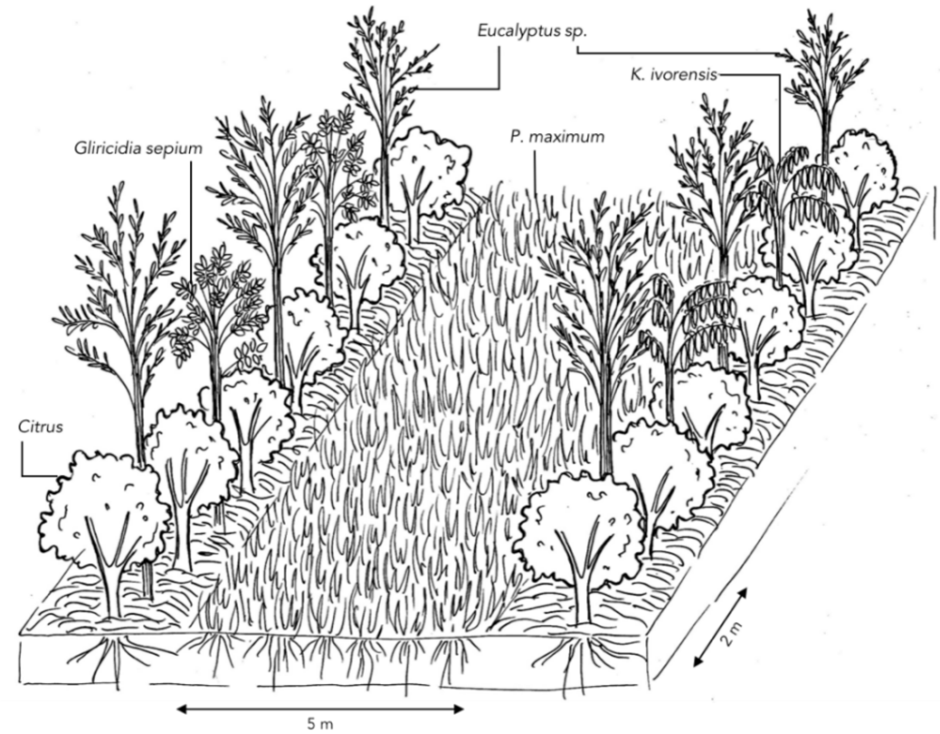

Figure 8 - Fazenda da Toca's SAFS on field 8, isometric. Spacing and overview at stage 3. Eucalyptus sp. is alternated with leguminous trees (Gliricidia sepium, Erythrina spp, Inga spp., Schizolobium parayhba) on one line, and with Khaya sp and Toona sp. on another line. In this simplified illustration all legume trees are represented by G. sepium and all timber trees by K. ivorensis.

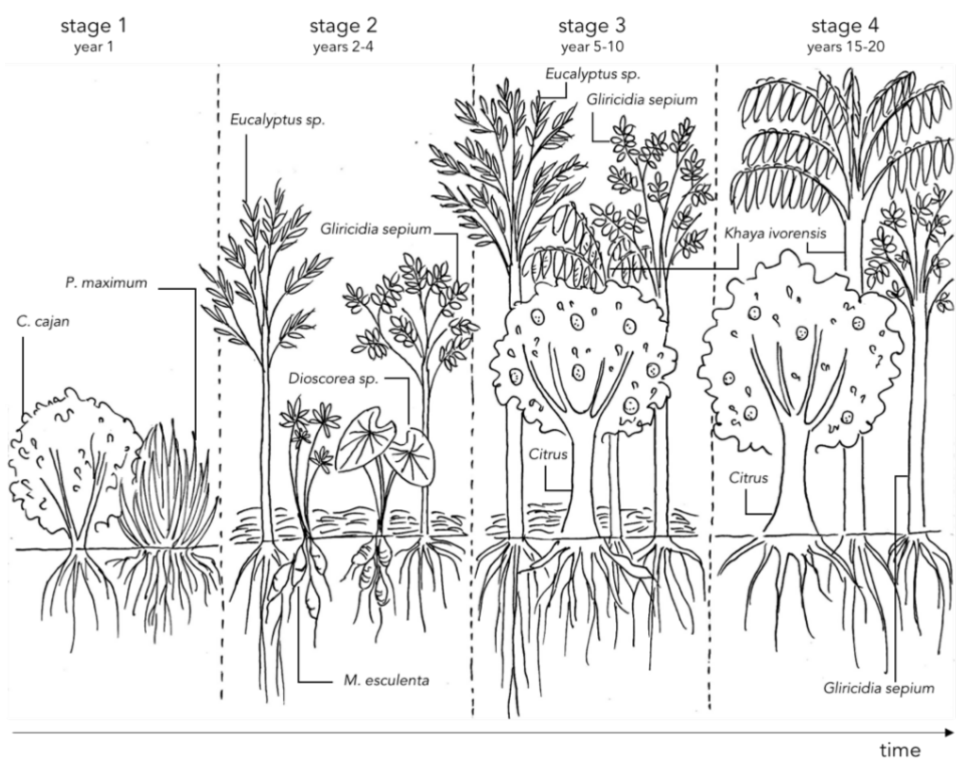

Figure 7 - Fazenda da Toca's SAFS on field 8, section. Impression of he successional stages on the tree line. Own elaboration.

2.2. Farm performance quantitative assessment: FarmDESIGN

FarmDESIGN and Data collection

In order to assess and predict the SAFS performance, and compare it with other farms, a whole-farm bio-economical modelling tool was used. FarmDESIGN is a model for the analysis and design of farming systems. Specifically, the functions 'describe' and 'explain' have been used in this study, in order to assess the farms' performance from both an environmental and economic perspective. The model was designed to describe and optimize mixed farming systems, this including crops and animals, but has proved to be generic enough to be used for a wide range of farm configurations in contrasting bio-physical conditions across different continents (Groot et al., 2012; Mandryk et al., 2014; Cortez-Arriola et al., 2016; Paul et al., 2015; Ditzler et al., 2019). Data regarding environment, economy and agronomy was collected on site at Fazenda da Toca, based both on observations and projections, given the recent implantation of the studies systems. The managers of the two comparison farms were interviewed for economic data collection.

Farm performance indicators

Indicators of the environmental and economic farm performance were chosen based on a farm and system objective analysis, on literature and on FarmDESIGN output (Table 2).

System objective	***Indicator***
Profitability	**Operating profit and Crop margin** (R$ ha^{-1} $year^{-1}$)
Low manual labour	**Labour requirement** (hours ha^{-1} $year^{-1}$)
High soil quality	**Average SOM balance** (kg ha^{-1})
High nutrient cycling	**Nutrient cycling ratio** (NPK taken up/NPK brought back)
High agro-biodiversity	**Shannon and Margalef indices**
High C sequestration	**Potential SOC accumulation rate** (Mg ha^{-1} $year^{-1}$)

Table 2 – Selected environmental and economic performance indicators and the relative objectives

A detailed objective analysis can be found in Results, while in the next section follows a detailed explanation of indicators, their relevance and how they are calculated.

SOM balance

Soil Organic Matter (SOM) is a key indicator for soil health, and increasing SOM percentage is one of the main objectives of regenerative farming systems (Rodale, 1983). FarmDESIGN provides the SOM balance as the difference between OM accumulation and losses. It is assumed that 80% of the OM added with green manures is degraded, and that the degradation rate of SOM as a whole is 2% per year. For a detailed explanation of the model calculations for the SOM inputs and outputs, see Groot et al. (2012). Soil Organic Matter balance could potentially be used as an indicator for both soil organic matter and water holding capacity, given the proven correlation between organic matter and water holding capacity in soils. Other factors being equal, soils richer in OM can retain more water and make more of it available to plants (Hudson, 1994).

SOC accumulation rate

Carbon sequestration is identified by Rizoma as one of the indicators for positive impact on the environment. Soil carbon sequestration is regarded as one of the most promising solutions for climate change mitigation (Minasny et al. 2007). While reducing the increase rate of atmospheric CO_2 concentration, C sequestration in the soil improves and sustains biomass and agronomic productivity (Lal, 2004). As an indicator for C sequestration, we calculate here the potential SOC accumulation rate, averaged over the 20 years of the system, considering exclusively the soil organic carbon that is potentially accumulated and not plant above and below ground biomass. SOC accumulation rate is calculated as follows:

$$Potential\ SOC\ accumulation\ rate = net\ SOM\ addition\ per\ year \times 0.58$$

where Potential SOC accumulation rate is the total organic carbon accumulated in a year in a given soil depth (Mg ha^{-1}), SOM is the soil organic matter added with OM inputs and green manures on average per year (kg ha^{-1} y^{-1}), and 0.58 is the conversion factor, assuming that SOM contains 58% carbon (Collins, 2001).

Nutrient (Re)Cycling

Nutrient cycling is defined as the flux of nutrients within and between biotic or abiotic pools in which nutrients occur in the environment (Brady & Weil, 2002). Here we focus on N, P and K and their cycles as provided by FarmDESIGN. There is no consensus on how to determine nutrient cycling in agro-ecosystems. In our case, we want to capture with this indicator the nutrients that are recycled within the system through service trees and grass biomass management as green manures. For this purpose, Nutrient Cycling is calculated as follows:

$$Nutrient\ Cycling\ ratio = \frac{Nutrient\ in\ Green\ Manure\ (kg)}{Plant\ nutrient\ uptake\ (kg)}$$

where Nutrient Cycling is the ratio between nutrients brought back to the soil with green manure through pruning, chopping and dropping (kg) and plant product (harvested or used as green manure) nutrient uptake (kg). Total inputs and outputs are provided by FarmDESIGN (Figure 9).

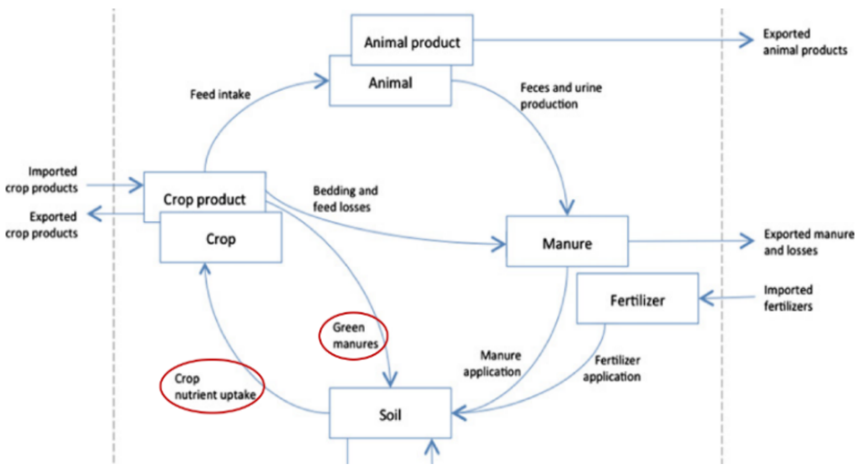

Figure 9 - Schematic representation of the FarmDESIGN farm model. Farm flows used for calculating Nutrient Cycling are circled in red. Adapted from Groot et al. (2012).

Agro-Biodiversity

FarmDESIGN does not provide the basis to analyse below ground biodiversity, which is ultimately what drives soil and agro-ecosystems' health and well-functioning (Bardgett and van der Putten, 2014). Nonetheless, Shannon and Margalef indices for above-ground biodiversity, part of the output of FarmDESIGN, can still provide insights. Shannon diversity index indicates diversity and evenness of distribution, and is higher when there is a significant number of different species with individuals in similar abundance. Margalef index addresses species richness and it increases when the number of species on the same area increases. Above-ground biodiversity suggests information about below-ground soil diversity. Belowground biodiversity is related to the heterogeneity of resources that plant species return to soil, affecting components and diversity of the soil biota and microhabitats (De Deyn & Van der Putten, 2005; Wardle et al. 2004). In the FarmDESIGN model, Shannon Index is calculated:

$$H_s = -\sum_{i=1}^{S} (p_i \ln (p_i))$$

where S = number of species, and p_i the share from one species in the total number of species.
Margalef index is calculated:

$$M = \frac{S-1}{\ln(N)}$$

where S is the number of species and N is the farm area expressed in m^2.

Operating profit, crop margin and labour requirements

The operating profit (R$) calculated with FarmDESIGN is the result of the crops margins minus the farm and crop costs (cultivation costs, labour costs, general costs) as described in detail by Groot at al. (2012). Considering the whole-farm nature of the model and the in-field focus of the study, also field revenues (margins) alone were considered, where these depend on revenues from crop products as affected by yield (kg) and selling price (R$ kg^{-1}), leaving out general farm costs.

Labour requirements are calculated as the total hours (hours ha^{-1} $year^{-1}$) of manual labour required on farm for all operations (e.g. planting, pruning, harvesting), including both regular and occasional labour and their respective prices $hour^{-1}$.

2.3. Function analysis and Functional Design Framework: RIO

Reflexive Interactive Design (RIO) was used to perform a function analysis of the existing SAFS and extrapolate functions and plant traits useful for a functional design framework. RIO is a systematic approach for the design of bio-systems, partly based on the Structured Design method (Van den Kroonenberg, 2002) (Figure 10). RIO consists of three steps: 1. System & actor analysis; 2. Structured design; 3. Anticipating niche & structural change. In this study we focus on steps 1 and 2, specifically on: E. Brief of Requirements; F. Key Functions; G. Morphological Function diagram; and, partly, H. Generation of solutions (Bos et al. 2009).

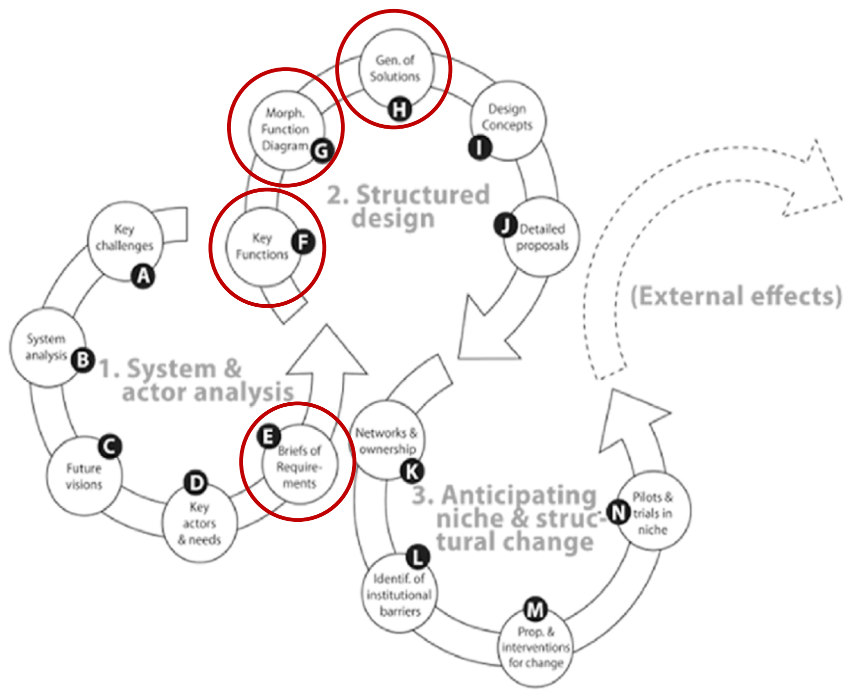

Figure 10 - Reflexive Interactive Design steps. Red circles highlight the steps we focus on in this study. Adapted from Bos et al. (2009).

The qualitative analysis of the case study SAFS was carried out through direct observations and semi-structured interviews. Preliminary interviews with SAFS experts were carried out to draft a first set of functions. Interviews with farm operation managers and researchers were carried out at Fazenda da Toca and at another small-scale farm applying SAFS. The aim of the semi-structured interviews was to know the objectives of the system, the functions performed by the plants and other system's elements, and the plants traits associated to the functions performance. Local and site-specific knowledge is the starting point of this function analysis, as scientific knowledge, especially in agriculture, needs a connection with local expertise of practitioners in order to complement academic knowledge and foster knowledge co-production (Andres et al., 2006).

Interviews were analysed with a content analysis (Erlingsson & Brysiewicz, 2017) and the results were complemented and backed up with expert knowledge and literature. Functions are expressed with a verb-plus-noun formulation as indicated in RIO. Together with plant ecology literature, the TRY database (www.try-db.org) was consulted to formulate plant ecological traits rephrasing interviews results. Feedback sessions with scientists, practitioners and various experts were done to receive and integrate feedback on the resulting framework. A list of interviewees and experts consulted can be found in Appendix 2.

3. RESULTS

3.1. Farm performance assessment

The case study farm: large-scale SAFS environmental and economic performance

The SOM balance of Fazenda da Toca's SAFS was found to be positive, with an average of 294 kg ha^{-1} net SOM added to the soil per year. The deriving potential SOC accumulation rate calculated is 0.17 Mg ha^{-1} $year^{-1}$, for a total accumulation of 3.4 Mg ha^{-1} over 20 years. The ratio between nutrients taken up and nutrients brought back to the soil as green manure was almost 1 (0.93 for N, 0.97 for P and 0.96 for K), confirming the high rate of nutrient cycling expected in the system. See Appendix 2 for detailed N, P and K nutrient cycles. Agro-biodiversity indices results for the two studied SAFS are 0.64 for Margelef index and 0.79 for Shannon index, with species numbers ranging from 5 to 10.
Regarding the economic performance, the calculated operating profit for the SAFS fields is 50,827 R$ ha^{-1} $year^{-1}$. The average labour requirement per hectare was found to be 582 hours ha^{-1} $year^{-1}$.

Indicator	Unit	Value
SOM balance	kg ha^{-1} y^{-1}	294
Nutrient Cycling	Ratio N cycled	0.91
	Ratio P cycled	0.97
	Ratio K cycled	0.96
SOC accumulation rate	Mg ha^{-1} $year^{-1}$	0.17
Agro-biodiversity	Margalef index	0.64
	Shannon index	0.79
Operating profit	R$ ha^{-1} $year^{-1}$	50,827
Labour requirement	Hours ha^{-1} $year^{-1}$	582

Table 3 - Fazenda da Toca's SAFS performance indicators results.

Economic performance comparison

The case study SAFS scored the best on operating profit, followed by the organic farm (42,578 R$ ha^{-1} $year^{-1}$), while the conventional farm had the lowest (32,000 R$ ha^{-1} $year^{-1}$) (Figure 11). Crop margin showed the same pattern, with the SAFS' one resulting approximately 2,000 R$ ha^{-1} $year^{-1}$ higher than the one of the conventional farm. Labour requirements, on the other hand, were found to be the highest in the SAFS (580 hours ha^{-1} $year^{-1}$) and the lowest in the organic small-scale farm (450 hours ha^{-1} $year^{-1}$).

Large-scale SAFS designs comparison

The two different SAFS designs performed slightly differently in environmental and economic indicators. In field 8, in which leguminous trees substitute banana plants, nutrient cycling was found to be on average higher, although the biomass added as green manure was slightly lower (Figure 12). Field 8 scored higher in biodiversity, with nearly double the species number than field 5. Labour requirements were found to be slightly lower in field 8 (Figure 13). This is due to high labour requirements of banana plants. Consequently, the economic margin is higher in field 8 than field 5.

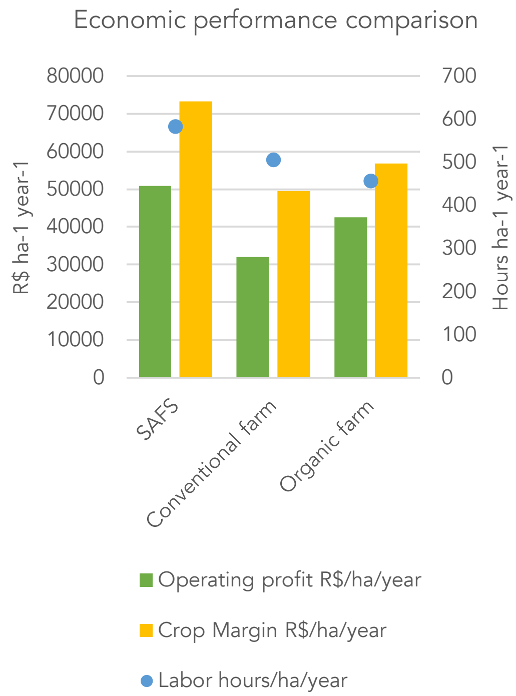

Figure 11 - Economic performance comparison of the three case study farms.

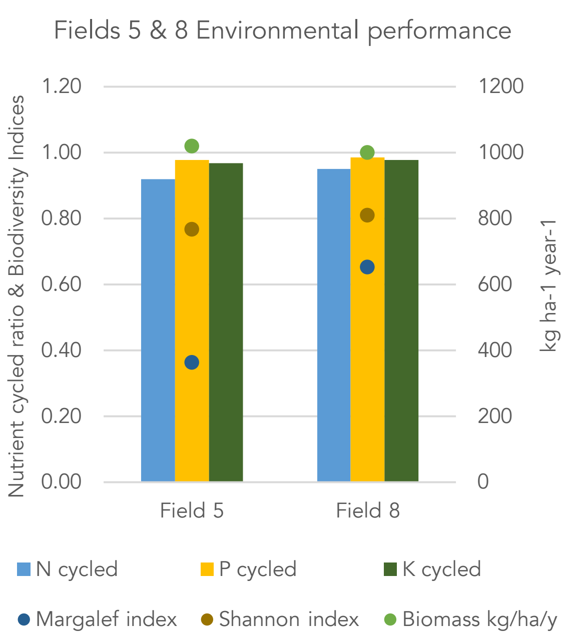

Figure 13 - Environmental performance of the two compared SAFS designs, field 5 and field 8.

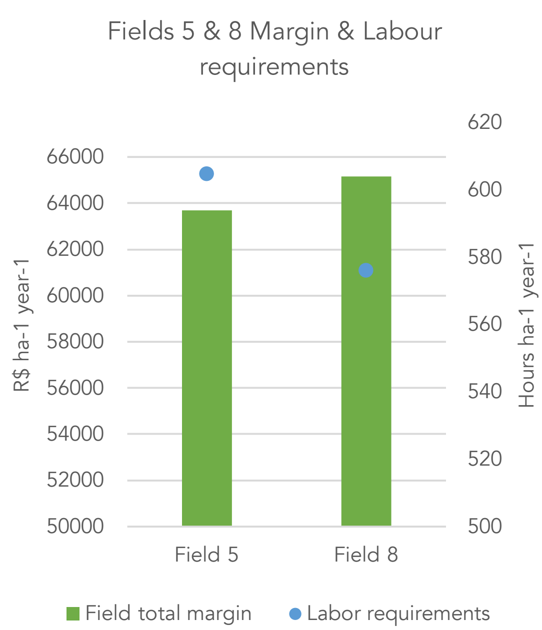

Figure 12 - Economic performance comparison of the two SAFS designs, field 5 and field 8.

3.2. Function analysis & Functional design framework

System's objectives

From the interviews, the case study large-scale SAFS objectives were drawn and interconnected. The system's objective identified is large-scale regenerative agricultural production, which is constituted by three main objectives: 1. Profitability; 2. Adaptability; 3. Positive impact on the environment. Each of these comes with a set of related sub-objectives and their inter-connections. As show in Figure 14, the objectives at every hierarchy level are correlated and linked to each other in a dense network. Positive impact on the environment, for the scope of this study and for the goals of the farm, translates into high soil quality and health, high nutrient cycling, high agro-biodiversity and high carbon sequestration.

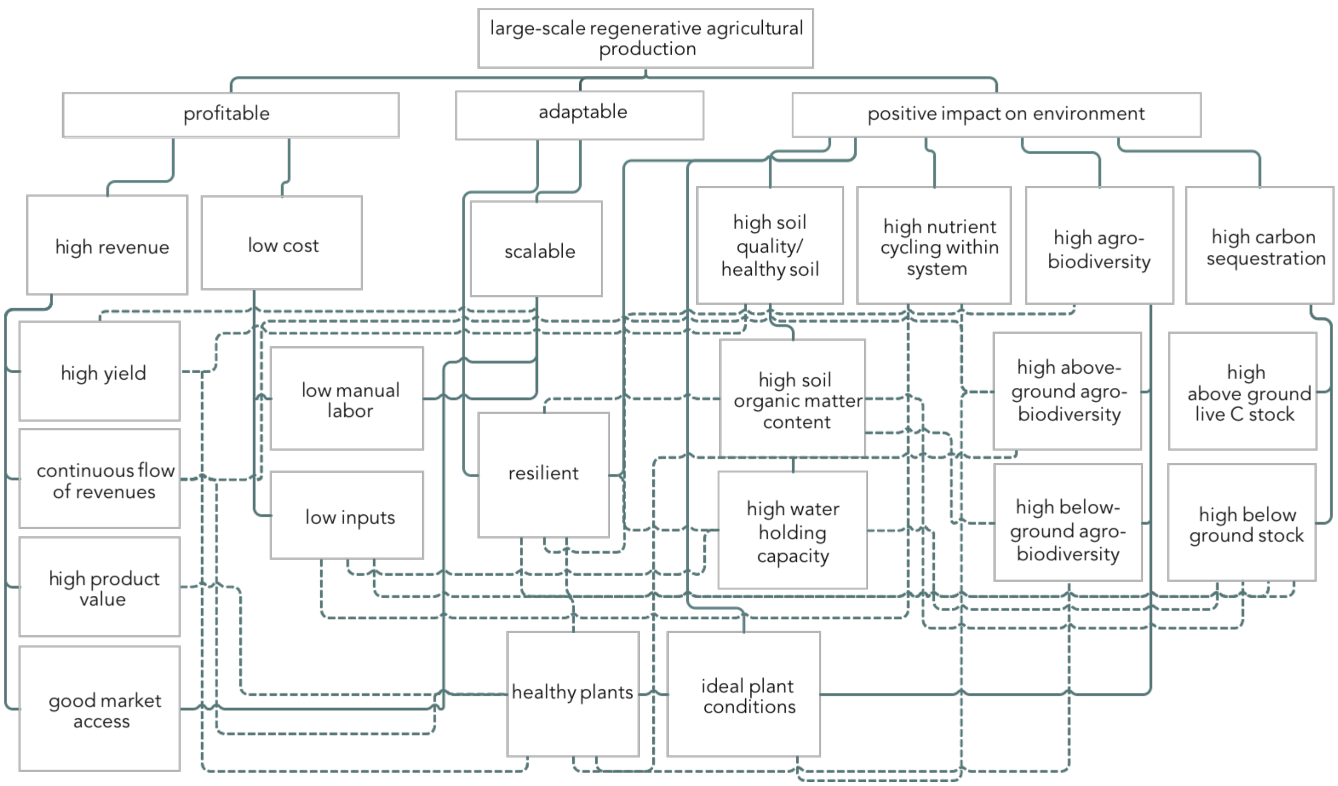

Figure 14 – Hierarchic flow-chart of the case study large-scale SAFS objectives. Full lines indicate hierarchical relations while dashed lines indicate sub-objectives inter-connections.

Requirements

Different contexts are characterized by different socio-economic and bio-physical conditions. These conditions determine a context-specific set of requirements which influences the performance of functions and the system's objectives. Requirements must thus be set for specific situations. An example of the case study SAFS brief of requirements can be found in Appendix 3.

Functions

The function analysis resulted in the identification of 13 functions with relative sub-functions, as illustrated in Figure 15. 'Produce biomass' emerged as one of the most important functions of service trees and it is here intended exclusively as the production of plant biomass to be used as green manure or as in-situ produced mulch. The sub-functions 'produce herbaceous biomass' and 'produce woody biomass' highlight the need of diverse plant material to be used as green manure/mulch, with the purpose of both increasing SOC sequestration (Dignac et al., 2017) and soil microbiota diversity (De Deyn & Van der Putten, 2005; Wardle et al. 2004). The biomass produced by plants needs to be harvested and distributed in order to be useful, thus the functions 'harvest' and 'distribute biomass'. In case of deciduous trees, these two could be performed by the plant itself. The function 'Input nutrients' is to be intended as addition of N, P, K and micronutrients from external sources. This includes fertilizers of any nature as well as atmospheric N fixed by plant species (mainly *Fabaceae*) in association with N-fixing bacteria. 'Make nutrients available', instead, refers to making nutrients already present in the system available to plants, as it happens with low-mobile P made available by mycorrhizae (Smith et al. 2011). The function 'Catch nutrients' is here composed by the sub-functions 'catch nutrients' and 'prevent nutrient loss'. The first one refers to nutrients which are already leaching out of the system, for instance in deeper soil horizons, while the latter to nutrients still in the top-soil or rhizosphere. 'Manage soil structure' function, particularly important in the first stages of system's establishment, includes 'break compacted soil' and 'aggregate soil particles'. These functions highlight the importance of soil structure in influencing plant health and productivity (Passioura, 1991) and SOC sequestration (Bronick & Lal, 2005), addressing both the objectives of 'Profitability' and 'Positive impact on the environment'. 'Cover soil' is a core function in agro-ecosystems that aim at mimicking nature (Malèzieux, 2011). Both living and dead mulch, as well as non-organic material, can fulfil this function.

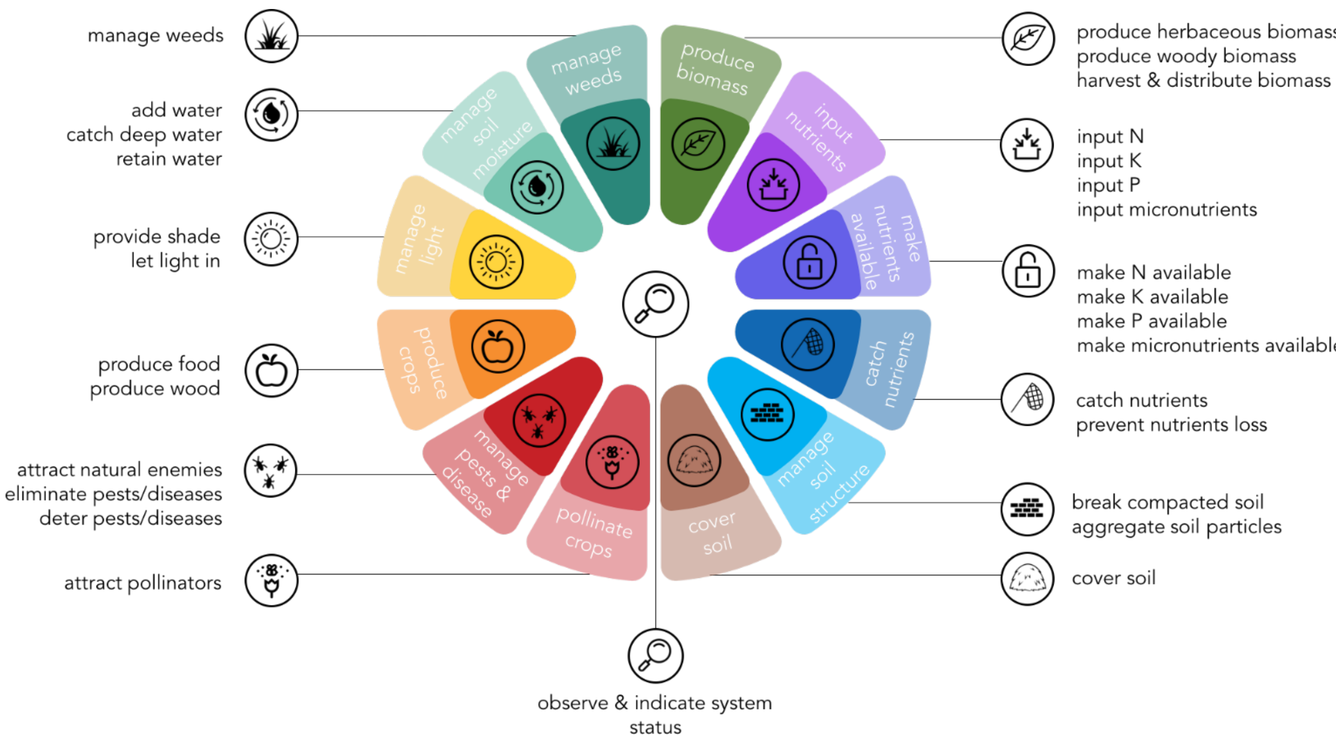

Figure 15 – The identified SAFS functions and their relative sub-functions. Own elaboration. Source for icons: www.thenounproject.com

This function is key in protection of soil from the direct influence of atmospheric events (Schulz et al. 1994). 'Cover soil' can also act as a solution itself for other functions such as 'Manage weeds' or 'Retain water'. 'Pollinate crops' addresses the importance of attracting pollinators (sub-function 'attract pollinators') for agricultural production (McGregor, 1976), and partly overlaps with 'Manage pests & diseases' when it comes to the provision of floral resources. The latter function, in fact, includes: 'attract natural enemies', via providing alternative food, alternative prey or shelter (Landis et al. 2000); 'eliminate pests/diseases', which can refer either to part or to the entirety of the community; 'deter pests/diseases', intended as prophylactic repellence of unwanted species. 'Produce marketable crops' addresses the need for the system to be economically sustainable, thus including marketable products such as food, wood, or others (biofuel, fibres) depending on the context. 'Manage light conditions' includes 'Provide shade' and 'Let light in' and acts as the main function referring to vertical stratification, plant light requirements and pruning management. 'Manage soil moisture' addresses the external addition ('add water') of water as well as the management of the water already in the system ('retain soil water') and of that exiting the system via percolation or run-off, or not yet available to the plants because stored in deeper soil horizons ('catch water'). 'Manage weeds' refers to the management or suppression of spontaneous vegetation. 'Observe & Indicate system's status' is a central function and addresses not only the presence of indicator elements, but also the importance of observation of the system to assess its status and act accordingly. This function points out the role of man in managed agro-ecosystems, which, however close to natural ecosystems, still have the objective to be productive and remunerative for people, therefore needing monitoring and management.

Traits

In order to fulfil given functions, plants need to display specific traits. The traits that were identified and selected as important in order to perform the needed functions in SAFS are listed in Figure 16, together with the associated function represented by an icon. In Appendix 4 a complete list of traits, associated functions and requirements can be found. In addition, a species list with specific traits and functions from the case study SAFS can be found in Appendix 5.

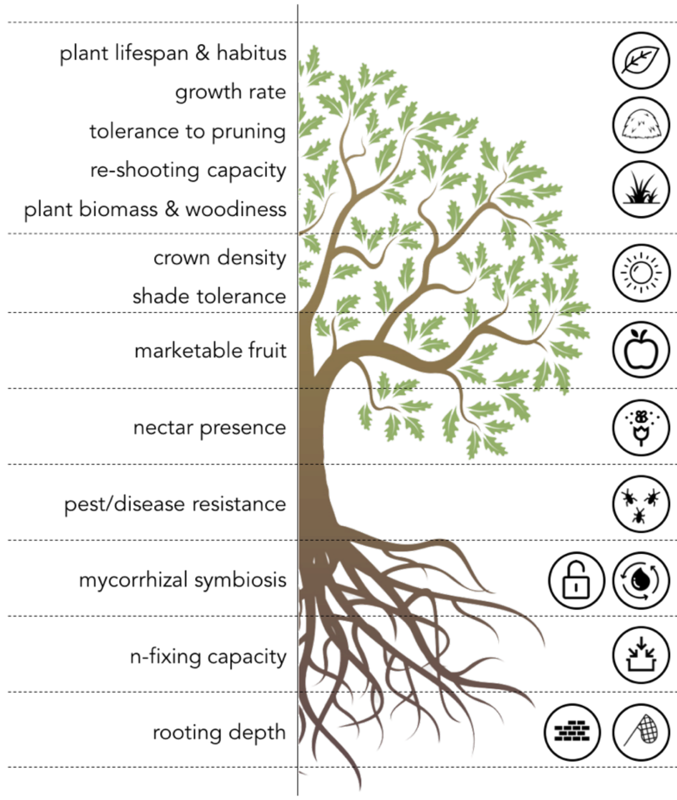

Figure 16 - List of traits with associated functions' icons. Own elaboration. Tree illustration: Illustration 55750463 © Rolandtopor – dreamstime.com

Morphological Functions diagram

With morphological functions diagrams, or morphological charts, a set of solutions can be explored to fulfil the needed functions. Solutions can vary greatly in nature and type depending on the context, and may include plants and biological entities as well as management practices. Table 4 shows the morphological diagram of existent solutions for Fazenda da Toca's SAFS. Morphological charts can serve as a check-list during the design process, and as a check-point along the development of SAFS. This tool must be complemented by the compatibility of species in space (vertical stratification) and time (successional stage). For this purpose, an iterative design process is advised, not only making use of functions, but also matching successional stages, life cycles and vertical stratification of the desired species community. Life-cycle matching includes not only the life span of plant species but also their compatibility in terms of agricultural operations, such as biomass management, fertilization, harvest.

A Successional Stage & Strata matrix was elaborated, based on Artzman (Personal communication), in which canopy layers are simplified to four main ones (emergent, canopy, sub-canopy, understorey) and four successional stages are considered. For each successional stage, the vertical layers occupied by the system's species are displayed, accompanied by the icons representing the functions they perform (see Figure 15 for an overview of functions). As a result, this diagram allows to combine the system's functions with the system's dynamics in space and time, with the possibility to serve as check-list for function fulfilment (Figure 17). Figure 17 provides an example from the case study SAFS plants of the Successional Stage, Strata and Functions matrix can be found.

Table 4 - Morphological Functions Diagram for the SAFS at Fazenda da Toca. Solutions are intended as the elements (plants) or management practices that perform the needed functions.

Icon	Function	Subfunction	Solutions				
	Produce biomass	**Produce herbaceous biomass**	*Panicum maximum*	*Musa sp.* *(banana)*			
		Produce woody biomass	*Eucalyptus urograndis*	*Inga spp.*	*Cajanus cajan*	*Gliricidia sp.*	*Erythrina spp.*
	Harvest biomass		Pruning of service trees with chain-saw	Grass mower for *P. maximum*			
	Distribute biomass		Manual distribution of tree biomass	Grass mower			
	Input nutrients	**Input N**	Chicken manure	*Cajanus cajan*	*Gliricidia sp.*	*Erythrina spp.*	*Azospirillum* inoculation
		Input K	Chicken manure				
		Input P	Chicken manure				
		Input micronutrients	Chicken manure	Boric acid	Fosfate	Zync sulfate	Manganese sulfate
	Make nutrients available	**Make N available**	*Eucalyptus* (deep rooting)	Green manure			
		Make K available	*Musa sp.*	Green manure			
		Make P available	*Manhiot esculenta*	*Dioscorea sp.*			
		Make micronutrients available	Green manure				
	Catch nutrients/Prevent nutrient loss	**Catch nutrients**	*Eucalyptus urograndis*	*P. maximum*			
		Prevent nutrient loss	*P. maximum*				
	Cover soil		*P. maximum* cuttings	*Eucalyptus* prunings	*P. maximum* cover crop	*Gliricidia sp.*, *Inga spp.*, *Erythrina spp.* prunings	
	Manage soil structure	**Break compacted soil**	*Cajanus cajan*	*Manhiot esculenta*	*Dioscorea sp.*		
		Aggregate soil particles	*Musa sp.*	*P. maximum*			
	Pollinate crops	**Attract pollinators**	*Cajanus cajan*	*Inga spp.*			
	Manage pests and diseases	**Attract natural enemies**	*Cajanus cajan*	*Inga spp.*			
		Eliminate pests/diseases	*Isaria fumosorosea* application (insecticide for HLB vector)	*Beauveria bassiana* application (insecticide for HLB vector)			
		Confuse/deter pests/diseases	*Musa sp.*	Above-ground diversification			
	Produce marketable crop	**Produce food**	*Citrus x latifolia*	*Manhiot esculenta*	*Dioscorea sp.*		
		Produce wood	*Khaya ivorensis*	*Toona ciliata*			
	Manage soil moisture	**Add water**	Drip irrigation				
		Catch deep water	Deep rooting Eucalyptus				

		Retain water	Green manure accumulation as mulch	Soil cover			
	Manage weeds		Green manure accumulation as mulch	Manual weeding	*P. maximum* cover crop		
	Manage light conditions	**Provide shade**	*Eucalyptus urograndis*	*Inga spp.*	*Khaya ivorensis*	*Gliricidia sp.*	Erythrina spp.
		Let light in	Pruning	Selective mowing of *P. maximum*	Spatial arrangement and layout		

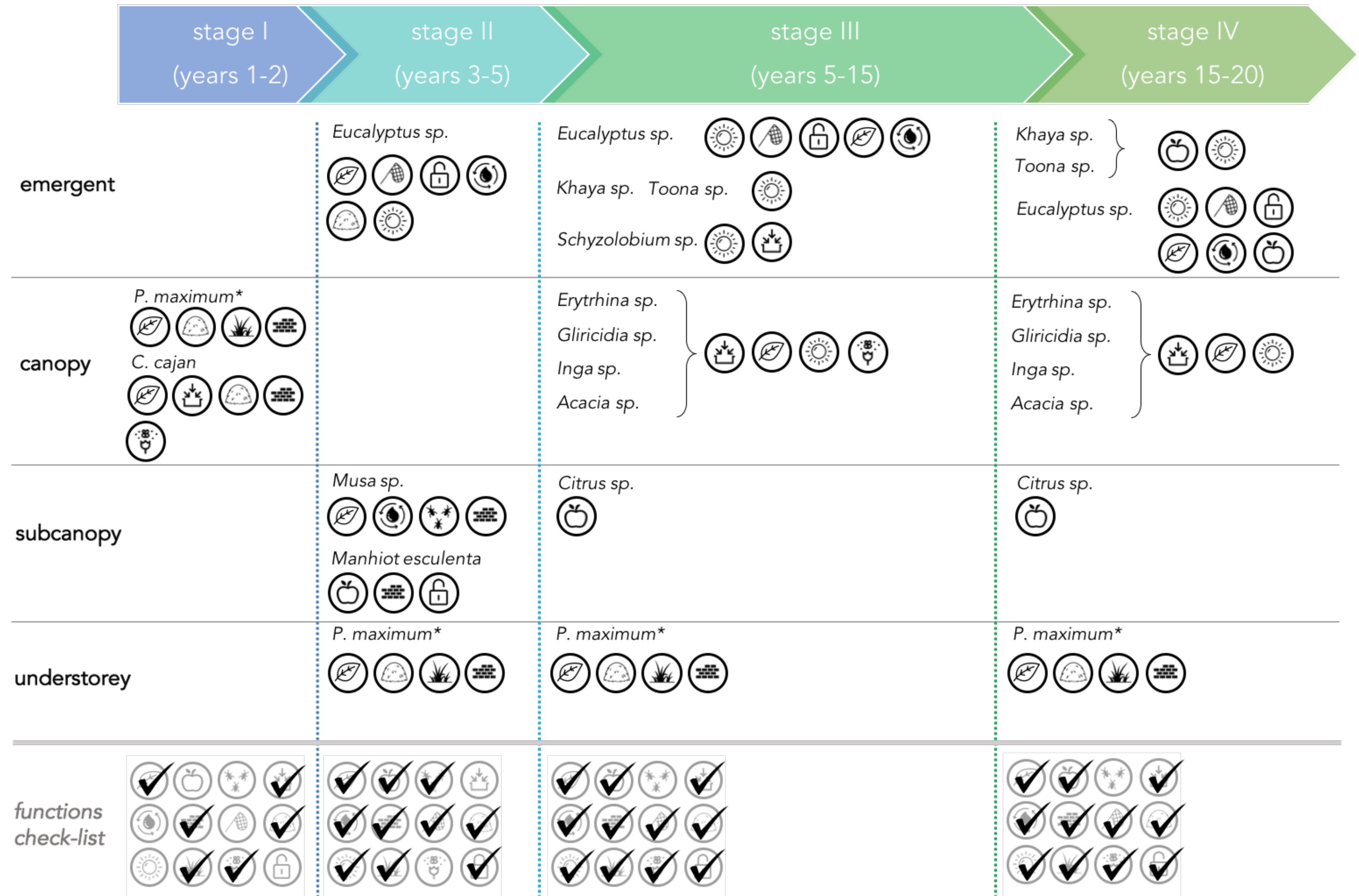

*Figure 17 - Strata, Successional stage & functions matrix for Fazenda da Toca's SAFS. This provides an example of what the final design decisions could look like. *Species indicated with an asterisk are planted on the strips between the tree lines. Own elaboration.*

4. DISCUSSION

4.1. Farm performance assessment

SAFS environmental performance

The positive SOM balance results for the Fazenda da Toca's SAFS (294 kg ha^{-1} $year^{-1}$) confirm the expected positive impact of the system on the environment. In fact, negative SOM balance values are common for tropical soils, where high temperatures and rainfall lead to very quick SOM decomposition, up to four times faster than in temperate conditions (Ross, 1993; Jenkinson and Ayanaba, 1977).

Our result for SOC increase rate of 0.17 Mg ha^{-1} $year^{-1}$ is directly and exclusively derived from the SOM balance result, therefore only accounting for C derived from organic matter addition, leaving out any other source such as plant roots or microorganisms. In fact, C sequestration in AF systems occurs in above-ground biomass and below-ground biomass besides in soil (Lorenz & Lal, 2014) and most studies on SOC sequestration in AF systems include plant root biomass C (Lorenz & Lal, 2014; Nair et al., 2010; Lal, 2004) or refer to static SOC pools (Jacobi et al, 2014; Gama-Rodriguez et al. 2010). Despite the difficulty in comparing our results with those of other studies, the value of 0.17 Mg ha^{-1} $year^{-1}$, including the sole SOC derived from organic matter addition, falls within the range 0.1 to 0.3 Mg ha^{-1} $year^{-1}$, which is the rate of SOC sequestration found in the humid tropics for AF including crop residue, leaf litter, root biomass and detritus material (Lal, 2004 b). This confirms the potential of large-scale SAFS for climate change mitigation, in strong contrast with mainstream agricultural practices. In fact, the conversion of tropical forest ecosystems to agricultural land uses has historically lead to a decline of the SOC pool to up to 20% of the antecedent pool (Lal, 2004 b). In general, increasing the amount of biomass C returned to soil though in-situ mulch production is recognized as a strategy to achieve higher SOC pools. However, the extent to which adding SOM through in-situ OM addition affects C stabilisation is unclear. Long-term C storage dynamics and C stability after C is sequestered in the soil are complex processes still not fully understood (Dignac et al., 2017).

The high nutrient cycling values that were found on the SAFS fields for N, P and K, with all values between 0.91 and 0.96, demonstrate that, at the system level, almost all nutrients taken up by plant species are brought back to the soil as green manure and mulch. These results suggest the possibility to drastically reduce external nutrient inputs, as reported in other studies on complex AF systems (Froufe et al. 2019; Vieria et al., 2009; Schulz et al. 1994). However, FarmDESIGN considers only 'crop products' (in our case, besides fruits, also plant biomass used as green manure) as outputs of nutrients; thus, in this picture, the nutrients taken up by and stored in citrus trees trunks and leaves, which do not leave the system nor are moved or recycled as green manure, are not included.

The agro-biodiversity indices resulted to be smaller than 1.00 (Table 3). Values above 2.00 were found in home-garden AF plots in Ethiopia, ranging between 2.26 and 2.43 (Linger et al., 2014). This is in line with the findings of Jacobi et al. (2014), who calculated a Shannon index of 2.3 for a SAFS in Bolivia. Nonetheless, the low Shannon and Margalef index values found for the case study SAFS are influenced by the surface-area-based approach used for the index calculation within the FarmDESIGN model. Indeed, in the linear SAFS design, the grass *P. maximum* is considered to occupy 80% of the surface, while the remaining 20% is used by the lines where all the other species are planted. This brings an imprecise and arbitrary area division amongst the tree species, which in this study we based simply on their number and frequency in the line, not considering their canopy or above-ground volume. Therefore, realistically, species evenness (Shannon index) is higher than what calculated using FarmDESIGN, which, as a simplified representation of reality, has been designed primarily for annual monocrops with clear area attribution.

Overall, the case study large-scale SAFS perform very well from the environmental perspective, not only producing food and wood but also providing ecosystem services. The large-scale SAFS meet the farm's objectives of SOC sequestration, high nutrient cycling within the system, high SOM content and consequentially water holding capacity. Nonetheless, although with uncertain results, biodiversity values are low compared to other SAFS. Indeed, a maximum of 12 plant species is used in the case study large-scale SAFS, while other studied SAFS can include up to 96 species (Jacobi et al., 2014). Although agro-biodiversity found in large-scale SAFS is considerably higher than in monocultures, it is still strikingly smaller than small-scale SAFS. The reduced agro-biodiversity of large-scale adaptations of SAFS can be seen as a result of the simplification strategies that allow scaling up and mechanization.

Economic performance and farms comparison

The case study citrus SAFS showed the highest operating profit and margin, proving that SAFS are viable and profitable agricultural systems on large-scale. Although yields are considerably higher in conventional citrus monoculture orchards than both organic monoculture and lime SAFS (Table 5), the selling price and the presence of secondary products such as tubers and timber seem to over-compensate for the yield gap, confirming that total system's productivity per hectare is higher in diversified agro-ecosystems, and crop diversification increases both environmental and economic resilience (Lin, 2011; Andres et al. 2016; Schneider et al., 2007; Niether et al. 2019). In fact, the returns on production of timber and cassava tubers account for 47% of the total returns of Fazenda da Toca's SAFS (Table 6), highlighting the potential of by-crops not only for self-consumption, as it is the case for small holders, but also for revenue (Armegot et al., 2016). Although Fazenda da Toca produces organic Tahiti lime, the difference in selling price between this farm and the organic monoculture farm can be attributed to the different market destinations that Rizoma adopts for the limes. The average selling price for the different product destinations (fresh product for the organic market, fresh product for the conventional market and limes for juice processing) is 1.27 R$ kg^{-1}.

As emerged in other studies, labour requirements for complex agroforestry systems are higher (Armengot et al., 2016; Jacobi et al. 2014), due to numerous and frequent manual operations such as biomass management and harvest of diverse produce, which are to date hard to mechanise. Labour is one of the main costs for these systems, but given the positive and high profit, it is not necessarily a negative factor. On the contrary, depending on the context, in economically sustainable systems it could also provide jobs and attract people to the rural areas (Angelsen & Kaimowitz, 2004). Labour-related results are, however, bound by the approximate nature of the data collection methods. Gathering information about labour hours with farmers who do not track labour consistently does not provide reliable and traceable data (Arthi et al., 2018). While Rizoma keeps detailed track of such information, for the conventional and organic comparison farms, approximations and assumptions based on oral communication were made. Nonetheless, this study's results are reliable in providing general trends.

Table 5 – Average yield and price of Tahiti lime on the three case study farms. For Fazenda da Toca the reported yield is projection.

	Unit	*Fazenda da Toca*	*Conventional farm*	*Organic farm*
Tahiti lime yield (20 year average)	t ha^{-1}	27	42	30
Price fresh limes	R$ kg	1.5	1.2	2.0

Table 6 – Projected returns in R$ ha^{-1} for the different crop products at Fazenda da Toca.

Crop	*R$ ha^{-1}*	*% of revenue*
Lime	78498	53
Cassava tubers	7750	5
Mahogany timber	62630	42
Total crop margin	148878	100

Designs comparison

Although all indicators results are very similar for the two different SAFS designs at Fazenda da Toca, some trends can be deduced from the differences. The main and most influential difference between the two designs appears to be the presence of either banana or leguminous trees. Field 5, with banana as one of the main green manure contributors, showed higher biomass production and higher labour input which seem to be related. Banana plants can produce great amounts of herbaceous biomass (up to 37 kg y^{-1} per plant) and the whole plant is cut back, chopped and distributed on the tree lines, manually, every two months. Labour costs are the reason behind the slightly lower margin found for field 5, compared to field 8. On the other hand, field 8, with five species of N-fixing trees, scored higher in nutrient cycling, suggesting that the green manure added, although inferior in weight, is richer in nutrients. Field 8 scored higher also in agro-biodiversity indices, as expected, given the higher number of species. Differences in planting densities may also have an effect on the results, being field 8 more dense in both lime trees and service trees. Overall, field 8, with leguminous trees, performs better both from the economic and the environmental perspective. These considerations are based on the assumption that yields and fertilization regimes are the same for both designs, because, although more citrus trees are present in field 8 (Table 1), they stay of smaller size because they are grafted on the Fly Dragon rootstock, a dwarfing variety of *Poncirus trifoliata*. Long term observations are needed to understand nutrient dynamics and the way they vary with different plants and set ups.

General observations on methods

The Tahiti lime SAFS at Fazenda da Toca have been recently planted and there is no stable yield yet. All input values for FarmDESIGN, such as yield, fertilization, pest control measures and products, profits, labor hours, etc., are predictions, mostly based on models developed and provided by Rizoma. Thus, all environmental and economic results are based on projections and not on real data based on on-farm observations and measurements. The study was meant to be carried out for established *Citrus spp*. SAFS, but all *Citrus spp.* trees, except those of most recent planting in the studied fields, were eradicated before the study started, in 2018.

Furthermore, FarmDESIGN is a modelling tool designed and tailored for mixed farming systems, these including animals and annual crops. Therefore, inputs and outputs are calculated on an annual basis. All parameters were averaged sums over the 20 years of the SAFS predicted life; thus, results are valid for an average theoretical year. Moreover, in FarmDESIGN only one soil type can be modelled, which is less realistic for large farms with high soil variety. Environmental data such as, for instance, bulk densitiy and texture, were therefore taken as averages of the fields' measurements considered.

While FarmDESIGN is intended as a whole-farm model, it is important to point out that the approach of this study was field-based for all the farms considered. Therefore, economic and financial data collected on farm, for instance general costs and machinery costs, may not be accurate as they refer to the whole farm use and not the isolated citrus SAFS or orchards. This also accounts for agro-biodiversity indices, which were calculated exclusively for the SAFS and orchards fields, and not for the whole farms.

All data concerning Fazenda da Toca, although mostly based on predictions, was collected on farm, while data regarding the conventional and the organic farms was collected via phone calls with the respective farmer and/or agronomist. Due to the difference in level of detail and timeframe in data collection, the information gathered on the organic and conventional citrus farms may be of reduced accuracy and reliability.

Quantitative modelling tools such as FarmDESIGN depict simplified versions of reality that fail to address processes that go beyond nutrients quantification and cycling. Processes such as communication of plants through the web of mycorrhizae, that allows exchange of nutrients, signals and allelochemicals inducing behavioral changes (Gorzelak et al. 2015) are not addressed by this type of tool, while they are considered as motors of the functioning of SAFS.

4.2. Function analysis & functional design framework

Function analysis: Objectives, functions and traits

The identified system's objectives (Figure 14) are, on one hand, specific to the case study's SAFS, but on the other hand are applicable and desirable in many other contexts. Specific objectives may be re-phrased, added or removed in particular cases, indicating the case-to-case objectives of the farmer in the farm context.

Broadly, functions needed for performing the system objectives in a wide array of biophysical environments, were identified (Figure 15). Most of the listed functions can be identified in any agro-ecosystem, but some of them are specific for SAFS, as for instance the biomass- and light-related ones. Functions can be performed by a wide array of elements within the system. In the case of SAFS, most functions are ideally performed by plants, in order to realise self-sustaining agro-ecosystems, thus with the least external inputs requirement (Schulz et al., 1994). Nonetheless, the same functions can be fulfilled by other elements or sourced from outside the system in less complex agro-ecosystems. Functions were compiled with the aim to build a framework as complete as possible rather than simplified, and some of the functions may result of less importance in some contexts (e.g. 'add water' in wet climates). Moreover, some functions may be fulfilled by the whole system thanks to its design, not only by specific plants. For instance, 'Manage pests & diseases', which in Figure 17 seems to be missing in most stages, is potentially fulfilled thanks to the agro-biodiversity of the SAFS as a whole (Kremen & Miles, 2012).

The set of thirteen functions, although aimed at covering the main features of SAFS, is specific for systems including exclusively plants. In the case of livestock presence, other functions such as 'Produce fodder' would be relevant. In other systems, 'Support other plants' as living trellis or fence, and 'reduce wind' could be relevant functions. The functions and sub-functions list, defined through interviews to practitioners, has been submitted for the feedback of other practitioners and experts and modified accordingly. Nonetheless, main interviewees were in relative low number (four, in multiple sessions) and a broader pool of SAFS practitioners or experts is needed to draw more generalizable conclusions. Although the sources were limited, the set of functions identified in this study provides a baseline covering the most important SAFS features, yet these can still be elaborated to provide a more generalised framework that can suit a wider set of cases.

The traits selected and mentioned in this study are addressed exclusively qualitatively. The scope and time-span of the study did not allow for further quantitative exploration. Functional-trait approaches to agricultural research remain, to date, poorly explored, and largely limited to pastures. Furthermore, there is a lack of functional-traits-related data for agricultural species and agro-ecosystems (Martin & Isaac, 2015). This is thus an interesting field for further research, especially in complex and dynamic agro-ecosystems such as SAFS.

Functional design framework

The function analysis performed on the large-scale SAFS resulted in a tool for designers and practitioners that can be generalised and applied in a wide array of biophysical environments. The tool, in the form of the functions set, the Morpholigical Functions Diagram, ant the Strata and Successional Stages matrix (Figure 17), can provide support in decision making and provide designers with a check-list in designing and realising SAFS.

Given the urgent need to spread regenerative practices and to radically redesign farming systems (Altieri et al., 2015), providing practitioners with applicable tools that support and facilitate the transition to complex agro-ecological systems is a key step. Moreover, this framework results from the aggregation of experts and practitioners' knowledge, resulting in an interactive co-learning process that helps refining knowledge for effectively scaling-up complex agroforestry systems (Coe et all., 2014). On the other hand, this framework cannot support design decisions alone. Environment, resources and markets (Artzman U., personal communication) are important starting points that must be taken into account.

Functional design framework application: a Mediterranean example

In order to test the use of the functional design framework, in this study it was applied to a different climate, namely the Mediterranean of Southern Europe, in a theoretical SAFS design trial. A Morphological Functions Diagram (Table 7) was filled in with a selection of species chosen to fulfil the identified functions for this theoretical design. The number of species selected can vary according to context-dependent conditions, scale, market access, labour-force and machines available. Thus, this same selection, could be expanded or reduced depending on the level of complexity and the scale desired. A more general morphological chart has been compiled, including a wider array of possible solutions (plants) for the chosen climate (Appendix 6).

Regarding the successional stages, a first stage (1 year) would see a cover-crop composed of intercropped wheat (*Triticum sp.*) and a legume (*Medicago sativa*) which can provide both a marketable product (wheat) and green manure to start accumulating mulch on the tree lines. After planting and seeding all other species, vegetables will dominate the second stage (years 2-4) between the tree lines, e.g. tomato (*Solanum lycopersicum*), cucumber (*Cucumis melo*), peppers (*Capsicum sp.*), lettuce (*Lactuca spp.*), depending on the desired complexity, diversification and market access, while fig tree (*Ficus carica*) and poplar (*Populus sp.*) will start growing fast on the tree lines, producing woody biomass that can be pruned, chopped and dropped on the lines. In the third stage (years 5-10), with tall enough trees to cast a shade between the lines, perennial N-fixing green manure will be planted (*M. sativa* or a cover crop mix including grasses such as *F. arundinacea* or *Avena altissima*) to be regularly cut and accumulated on the lines, while pomegranate (*Punica granatum*) and fig tree enter in full production, together with artichoke

(*Cynara cardunculus*) and aromatic plants (*Rosmarinus officinale*). Depending on the chosen variety, olive tree (*Olea europaea*) will come to full production after 5-10 years, dominating the last stage (11-30+).

Figure 18 shows the dynamics in space (vertical stratification) and time (successional stages) of the selected plant community. A full species list with specific traits associated to the functions from the Mediterranean theoretical application example can be found in Appendix 7. We limit the theoretical explorations to suitable species and their life-cycles and strata interactions. Design specifics such as spacing and densities require an in-depth effort and a context specificity which is beyond the scope of this theoretical application trial.

Table 7 - Morphological Functions Diagram of the selected plants for the theoretical framework application for the Mediterranean climate

Icon	*Function*	*Subfunction*	*Solutions*				
	Produce biomass	**Produce herbaceous biomass**	*Triticum spp.*	*Vicia faba*	*Medicago sativa* cover crop		
		Produce woody biomass	*Populus spp.*	*Ficus carica*			
	Harvest biomass		Pruning of *Populus spp.* and *Ficus*	Cutting/mowing of leguminous cover crops			
	Distribute biomass		Manual distribution of woody biomass	Mechanical distribution of herbaceous green manure			
	Input nutrients	**Input N**	*V. faba*	*Medicago sativa*			
		Input K	Green manure				
		Input P	Green manure				
		Input micronutrients	Green manure				
	Make nutrients available	**Make N available**	*Ficus carica*	*Populus spp.*			
		Make K available					
		Make P available					
		Make micronutrients available					
	Catch nutrients/Prevent nutrient loss	**Catch nutrients**	*Ficus carica*	*Populus spp.*			
		Prevent nutrient loss	*Triticum spp.*				
	Cover soil		*Triticum spp.*	*Vicia faba*	*Medicago sativa*	*Ficus carica*	*Populus spp.*
	Manage soil structure	**Break compacted soil**	*Triticum spp.*	*Cynara carduncului*			
		Aggregate soil particles					
	Pollinate crops	**Attract pollinators**	*Rosmarinus officinalis*	*Salvia spp.*			
	Manage (balance) pests and diseases	**Attract natural enemies**	*Rosmarinus officinalis*	*Salvia spp.*	*Punica granatum*		
		Eliminate pests/diseases					
		Confuse/deter pests/diseases	Above-ground diversification	*Rosmarinus officinalis*	*Salvia spp.*		

Produce marketable crop	**Produce food**	*P. granatum*	*Ficus carica*	*Cynara cardunculus*	*Solanum sycopersicum; Cucumis sativus; Lactuca sativa*	*Olea Eropaea*
	Produce wood	*Olea Europaea*	*Populus spp.*			
Manage soil moisture	**Add water**					
	Catch deep water	*Ficus carica*	*Populus spp.*			
	Retain water	Mulch				
Manage weeds		*Triricum sp.*	*Medicago sativa*	*Vicia faba*	*Mulch*	
Manage light conditions	**Provide shade**	*Populus spp.*	*Ficus carica*			
	Let light in					

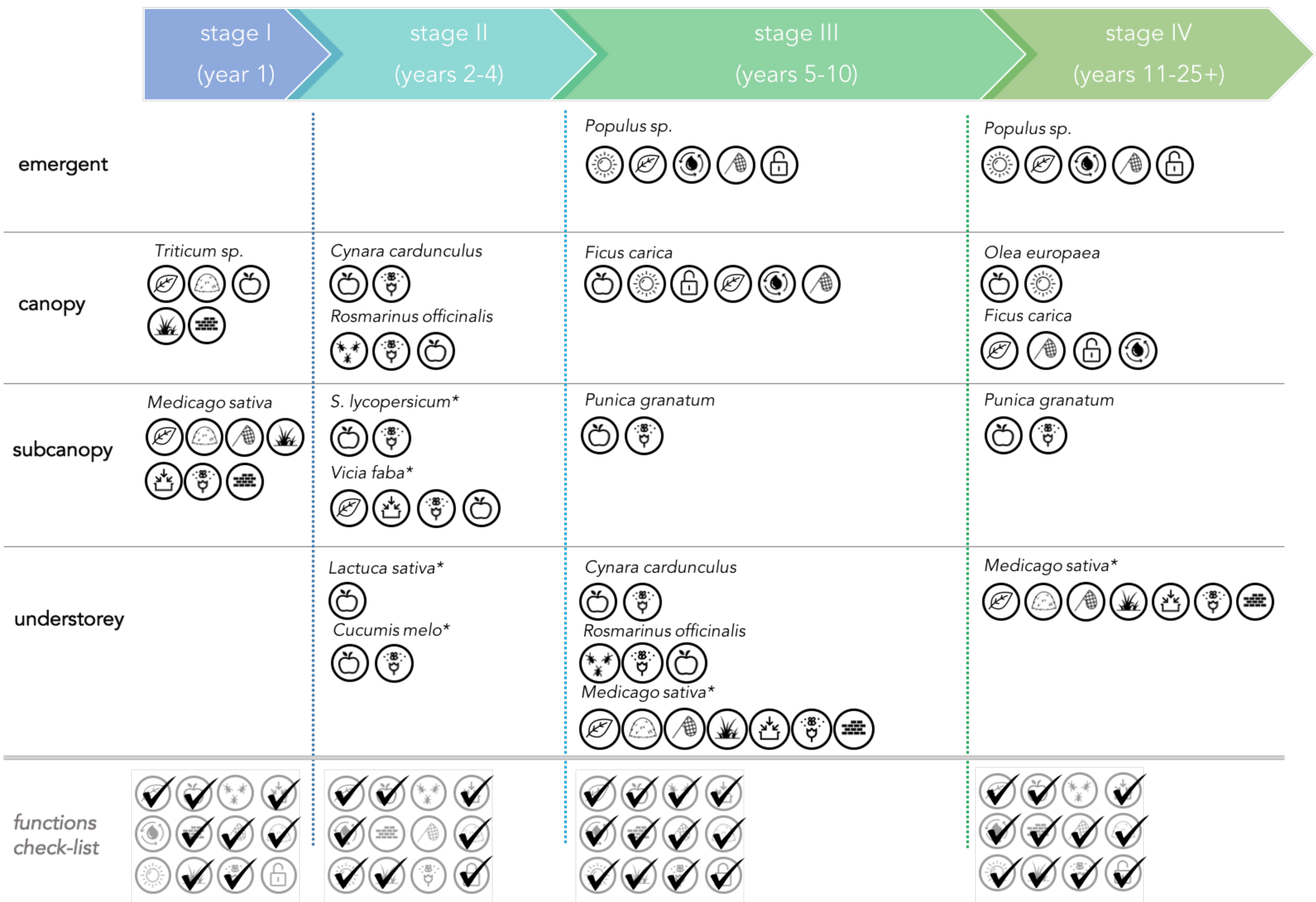

*Figure 18 - Strata, successional stages and functions matrix of the theoretical framework application to the Mediterranean climate. *Species indicated with an asterisk are planted between the tree lines. The others are all on the tree line.*

4.3. Recommendations and further research

Although FarmDESIGN resulted useful in understanding general trends, specific models addressing the complexity of agro-ecosystems such as AF systems still need to be developed. More research on ecological processes such as nutrient cycling in complex systems, and plant nutrient and information sharing through mycorrhizal networks in agro-ecosystems, is needed. Moreover, large-scale adaptations of complex SAFS come at the cost of diversification, but to what extent it is possible to simplify the system without reducing environmental benefits is still unclear. Furthermore, machines for complex agro-ecosystems like SAFS need to be developed in order to facilitate the scaling up of SAFS.

Designing SAFS, whether or not facilitated by tools such as the Functional Design Framework, requires pre-requisite knowledge on natural ecosystems and local plant species pools to choose from for design. Existing databases and literature on spontaneous vegetation are not sufficient in providing the necessary information for the design of complex, agro-ecological farming systems. Some databases for plant species to be used in agro-ecosystem design are available online, but are often incomplete, lack geographical references, cover only restricted geographical areas or climates and often lack scientific basis. Specific information on species that can potentially grow in a certain place and their agro-ecological characteristics (e.g. life cycles, vertical stratification, functions, management) is needed to facilitate the spread and scaling-up of SAFS and other complex agro-ecosystems. Moreover, despite the increasing interest in trait-based approaches to acro-ecosystems (Darmour et al. 2017), there is a lack of functional-traits-related data for agricultural species and agro-ecosystems (Martin & Isaac, 2015).

Farming systems are embedded in the complex matrix of the global food system (Kremen et al. 2012), and their shift towards regenerative models must be accompanied by radical changes that range from governance (IPES-Food, 2017) to global diets (Willet et al., 2019). Therefore, redesign is not only an agricultural challenge, but also a social and institutional challenge (Pretty et al., 2018), and must be addressed in research and practice at all levels of the food system.

5. CONCLUSIONS

The case study large-scale SAFS perform well both from the economic and the environmental perspective, producing food and wood profitably while having a positive net impact on the environment. The large-scale SAFS proved to increase SOM, sequester SOC and cycle nutrients at high rates within the agro-ecosystem. Agro-biodiversity of SAFS is relevantly higher than monocultures; however, it is lower than small-scale SAFS, due to simplification of the system that allows mechanization and products sales in large quantities. Although lime yields were found to be lower in SAFS than in conventional and organic monocultures, the selling price and the presence of by-crops such as timber and tubers over-compensate for the yield-gap, securing high profits. Labour requirements are the highest in SAFS due to manual biomass management. Nonetheless, differences in SAFS designs and species choice was shown to influence labour costs and nutrient cycling (external inputs requirements), suggesting that adjustments in the desired direction are possible within SAFS. This study demonstrates that large-scale complex agro-ecosystems such as SAFS not only provide ecosystem services but are also economically viable, thus offering a valid alternative to the industrial agricultural uniformity, and a model for large-scale redesign.

The set of functions and relative sub-functions identified in this study, based on the identified SAFS objectives, provide a baseline covering the most important SAFS features, but can still be elaborated to provide a more generalised framework that can suit a wider set of cases. A Functional Design Framework for replication of SAFS, constituted by the set of functions, morphological charts and the stages and strata diagram, was designed, and proved to be useful in designing SAFS across different bio-physical contexts. Nonetheless, the framework requires real-life trials to be tested and adjusted, and specific geographical databases for agro-ecosystems design are needed to complement the use of this design tool.

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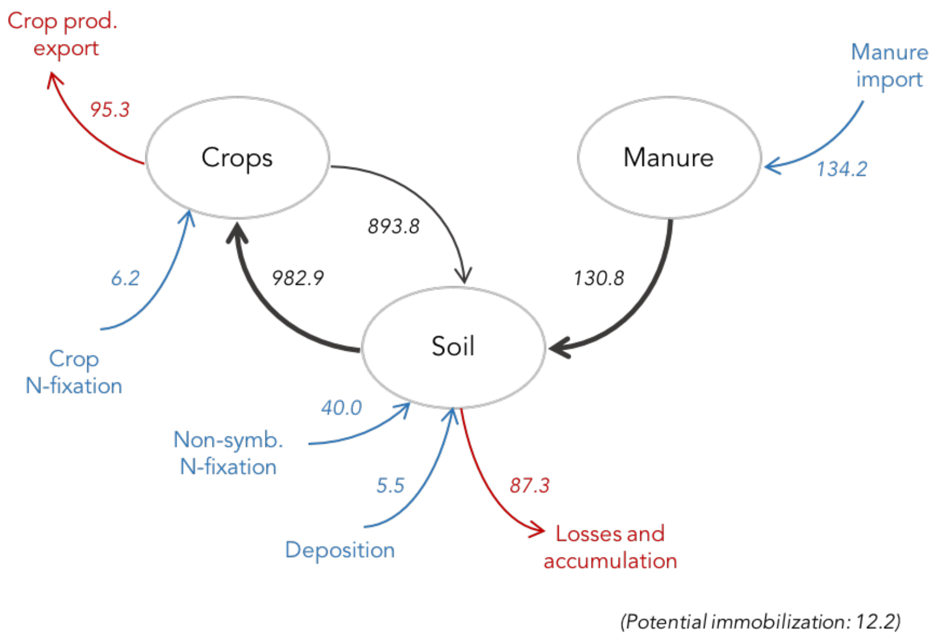
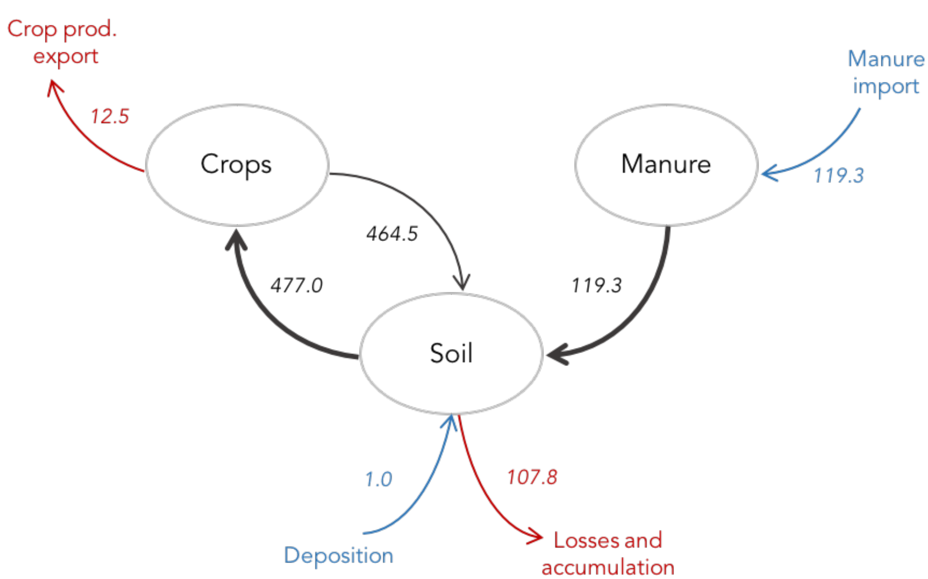
APPENDIX

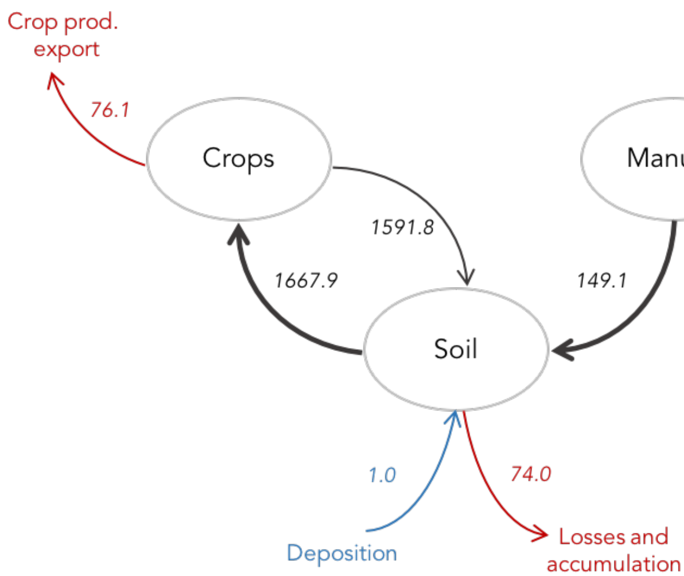
1. Nutrient cycles from FarmDESIGN, Fazenda da Toca's SAFS



Appendix Figure 1 - Nitrogen cycle of Fazenda da Toca's SAFS, adapted from FarmDESIGN output



Appendix Figure 2 - Phosphorus cycle of Fazenda da Toca0s SAFS, adapted from FarmDESIGN output



Appendix Figure 3 - Potassium cycle from FarmDESIGN output

2. List of contributors

Interviewees

- Ursula Artzman, Soulfood farms (Antigua), previously Life in Syntropy
- Felipe Noronha, Rizoma (Brazil)
- Osvaldo Viu Serrano Junior, Rizoma & Fazenda da Toca (Brazil)
- Paulo Roberto da Rocha Junior, Rizoma (Brazil)
- Karin Hansi, Epicentro Dalva (Brazil)

Experts consulted & Feedback session participants

- Giuseppe Sannicandro, Naumanni Permacultura Migrante (Italy)
- Frank Sterck, Wageningen University & Research
- Jonas Stainfeld, Wageningen University & Research
- Benedikt Bösel, Alt Madlitz (Germany)
- Pieter Groot Koerkamp, Wageningen University & Research
- Tatiana Moreira, Wageningen University & Research

3. Brief of requirements, Fazenda da Toca's SAFs

No.	Requirement	Requirement set by	Related Function	Related plant trait	Rationale & References
1	Produce > 900kg/ha/year of biomass on the lines. Growth rate 2-5 m/year for biomass producing species.	Environment/Farmer	Produce biomass	Plant aboveground biomass wet/dry weight Plant growth rate Reshooting capacity Tolerance to pruning/mowing Habitus	990 kg/ha is the current lowest average annual biomass addition (for Field 8). (Personal communication, Rizoma) The minimum requirements for in-situ biomass production are an open question. Nonetheless, the biomass produced needs to be sufficient for permanently covering the soil on the tree lines with a thick mulch of at least 20 cm (Foshee et al., 1996).
2	Add both herbaceous and woody biomass	Farmer	Produce biomass Distrubute biomass	Plant woodiness	Soil biodiversity is directly associated with plant material diversity reaching the soil. (De Deyn & Van der Putten, 2005; Wardle et al. 2004).
3	N input approximately between 300 and 400 g/tree/year, depending on production class, soil type and leaf N.	Crop	Input nutrients (N)	N fixation capacity	Nutrient requirements vary within this range with the age and the density of an orchard, and across different soils and environments. (Mattos et al. 2012; Boaretto et al. 2006)
	-	Crop	Input nutrients (P)	-	Yield responses for P and K applications were observed respectively in soils with less than 20 mg dm^{-3} of P and 2.0 $mmol_c$ dm^{-3} of K^+ (Quaggio et al. 1998). Soils at Toca have an average of 64 mg/dm3 of P and K levels above 2.7 mmol/dm3.
	-	Crop	Input nutrients (K)	-	
4	Mycorrhizal network presence	Farmer/Envrinoment	Make nutrients available	Mycorrhizal symbiosis	Citrus is highly dependent on mycorrhizae and can host 45 species of AMF. (Wu et al. 2016); Mycorrhizal networks (MNs) link multiple plants belowground and can influence plant establishment, survival and growth. MNs serve as interplant exchange of resources and molecules. Plants that are connected via a MN can modify their behaviour in response to fungal colonization and interplant biochemical communication with responses that include root growth and shoot growth (Gorzelak et al. 2015).
5	Roots grow deeper than the top-soil and first soil layers (>1m)	Environment	Catch nutrients	Rooting depth	Deep roots can work as a safety-net: they catch nutrients leached from the topsoil and transfer those available in deeper horizons to the top soil (Da Silva et al. 2011). Maeght et al. (2013) proposed that 'deep roots' can be considered as those growing deeper than 1m, based on Schenk and Jackson's study (2002) that estimated a median depth of root profiles of 0.88 m. Although this is an oversimplification, Pierret et al. (2016) concluded that considering plant roots associated with biogeochemical processes of soils,

					the 1m proposition could still be insightful.
6	All Perennial species	Farmer; environment; management	Manage soil structure	Rooting depth Root volume/area	Perennial plants allow no-tillage management and improvement of soil quality over time.
7	20cm thick constant soil cover or living mulch	Farmer; Environment	Cover soil Manage weeds	See 'Produce biomass' associated traits	A thick layer of much (at least 20cm) allows optimal weed control and sufficient addition of organic matter. (Foshee et al., 1996; Personal communication, Rizoma)
8	Pollinators presence in September and October (Citrus blossoming time)		Pollinate crops	Nectar presence	The presence of nectar is significant for attracting pollinators and natural enemies for indirect defence (Nepi et al. 2018).
9	HLB infected plants <10%	Farmer	Manage pests	Disease/Pest tolerance Host natural enemies	Production is not significantly affected with infection rates equal or smaller than 10% (Rizoma, personal communication)
10	Marketable crops revenue > whole systems costs	Farmer	Produce crops	Bear marketable fruit/wood	The revenue from the main crop(s) needs to pay off for all the operations of the other system's elements like service trees.
11	Shade percentage between 0 and 40% depending on stage. Full sun required during blossoming & fruit set (September-October)	Crop	Manage light conditions	Shade tolerance Crown density Habitus (deciduous/evergreen)	*Citrus sp.* occupies a sub-canopy stratum and benefits from moderate shade of approximately 30% (Cohen et al., 1997; Jifon & Syvertsen, 2003).
12	Plant with roots deeper than 1m	Environment	Catch deep water	Rooting depth	"During the dry season, the deep soil compartment can contribute to as much as 83% of the total water used in a tree-dominated Cerrado community." (Oliveira et al., 2005) Nonetheless, roots can extend to at least 18 m in Cerrado vegetation (Rawitscher 1948). Water uptake has been reported up to 8 metres deep for Eucalyptus in Brazil (Christina et al. 2011)
13	100mm of water per month	Crop	Add water	Plant biomass water content	Personal communication from Rizoma (current irrigation 7mm every 2 days)

4. Traits

Trait	*Associated Function*	*Requirement example*
Rooting depth	Catch nutrients; Prevent nutrient loss; Catch deep water	Roots grow deeper than 1m
Shade tolerance	Manage light conditions	Tolerates 40% shade
Crown density	Manage light conditions	Sparse crown
Growth rate	Produce biomass; cover soil	Grows 2-5 m/year
Pest and disease resistance/tolerance	Manage pests/diseases	HLB infection on < 10% of plants
N fixation capacity	Input nutrients	N input 300g/tree/year
Mycorrhizal symbiosis presence	Make nutrients available; Manage soil moisture	Mycorrhizal Network presence
Nectar presence	Pollinate crops	Pollinators presence in Sept-Oct
Plant woodiness	Produce biomass	Perennial species
Plant aboveground biomass	Produce biomass	900kg/ha/year of biomass input
Plant lifespan	Produce biomass; Manage light conditions;	Compatible plant life cycles and strata. Quantitative requirements differ per crop combination.
Tolerance to mowing	Produce biomass; Harvest biomass	Presence
Re-shooting capacity	Produce biomass; Harvest biomass	Presence
Tolerance to pruning	Produce biomass; Harvest biomass;	Presence
Presence of marketable fruit	Produce marketable crop	Presence
Habitus (deciduous/evergreen)	Manage light conditions; produce biomass; harvest biomass	Full sun during blossoming season
Leaf shredding time	Manage light conditions	Full sun during blossoming season

*Extracted from interviews and feedback sessions, and rephrased based on TRY database

5. Case Study SAFS plants' traits & functions

Plant	Functions	Traits
Citrus x latifolia	Produce marketable fruit	Bears fruit; Shade tolerance
Panicum maximum	Produce (herbaceous) biomass Manage weeds Cover soil Manage soil structure	Fast growing Perennial Tolerance to mowing Deep and extended fasciculate root system
Cajanus cajan	Input nutrients (N) Produce (woody) biomass Cover soil Break soil (Manage soil structure)	Fast growing N fixing capacity Woody
Musa sp.	Produce biomass Aggregate soil particles (Manage soil structure) Manage pests Cover soil Manage soil moisture	Fast growing Tolerance to pruning Perennial Contains mucilage Hosts natural enemies
Eucalyptus urograndis	Produce (woody) biomass Catch nutrients/Avoid nutrients loss Catch deep water (Manage soil moisture) Make nutrients available Manage light conditions (Shade other plants) Produce timber	Fast growing Deep roots up to 20-30 m Hydraulic lifting capacity (Christina et al. 2011) Sparse crown
Inga spp. *Gliricidia sepium* *Erythrina spp.* *Acacia mangium*	Produce (woody) biomass Input nutrients (N) Manage light conditions Attract pollinators	N fixing capacity Tolerance to pruning Perennial woody species Canopy layer Extra-floral nectar resources (*Inga* sp.)
Khaya ivorensis *Toona ciliata*	Produce marketable wood Manage light conditions	Marketable wood Matching life cycle with main crop Occupy canopy/emergent layer
Dioscorea sp. *Manihot esculenta*	Produce marketable roots Manage soil structure Make nutrients available	Marketable tubers Foster mycorrhizal symbiosis

6. Mediterranean morphological chart, general

Function	*Subfunction*	*Solutions*					
Produce biomass	**Produce herbaceous biomass**	*Lupinus sp.*	*Vicia faba*	*Miscanthus so.*	*Panicum sp.*	*Hordeum vulgare*	*Avena sp.*
	Produce woody biomass	*Robinia pseudoacacia*	*Ficus carica*	*Ailanthus altissima*	*Eucalyptus sp.*	*Populus sp.*	*Fraxinus sp.*
Harvest biomass							
Distribute biomass							
Input nutrients	**Input N**	*Robinia pseudoacacia*	*Acacia saligna*	*Elaeagnus sp.*	*Medicago sativa*	*Alnus sp.*	*Acacia dealbata*
	Input K						
	Input P	*Symphytum sp.*					
	Input micronutrients	*Allium sp.*					
Make nutrients available	**Make N available**	*Urtica sp.*	*Brasicaceae*				
	Make K available	*Casuarina sp.*					
	Make P available						
	Make micronutrients available						
Catch nutrients/Prevent nutrient loss	**Catch nutrients**	*Ficus carica*	*Eucalyptus spp.*	*Populus spp.*			
	Prevent nutrient loss	*Hordeum sp.*	*Avena sp.*	*Triticum sp.*	*Chrysopogon zizanioides*		
Cover soil	**Cover soil**	*Lippia repens*	*Rubus fruticosus*	*Fragaria sp.*			
Manage soil structure	**Break compacted soil**	*Sinapis sp.*	*Canapa sp.*	*Malva sylvestris*	*Althea sp.*	*Mirabilis jalapa*	*Raphanus sativus L. var. longipinnatus Bailey*
	Aggregate soil particles	*Opuntia ficus-indica*	*Pistacia lentiscus*				
Pollinate crops	**Attract pollinators**	*Cornus mas*	*Amelanchier ovalis*	*Evodia danielli*	*Robinia pseudoacacia*	*Taraxacum officinalis*	*Hedera helix*
Manage (balance) pests and diseases	**Attract natural enemies**	*Inula viscosa*					
	Eliminate pests/diseases	*Artemisia absinthium*					
	Confuse/deter	*Geranium spp.*	*Salvia offiinalis*				

	pests/diseases						
Produce marketable crop	**Produce food**	*Prunus dulcis*	*Ficus carica*	*Olea europaea*	*Cynara cardunculus*	*Prunus avium*	*Rosmarinus officinale*
	Produce wood	*Paulownia sp.*					
Manage soil moisture	**Add water**	*Opuntia ficus-indica*					
	Catch deep water	*Eucalyptus sp.*	*Populus spp.*	*Celtis australis*	*Ficus spp.*		
	Retain water	*Opuntia ficus-indica*					
Manage weeds		*Avena spp.*	*Medicago sativa*				
Manage light conditions	**Provide shade**	*Robinia pseudoacacia*	*Eucalyptus spp.*	*Ailanthus altissima*	*Populus spp.*	*Platanus spp.*	*Tilia spp.*
	Let light in	Management: pruning					

7. Species list, functions and associated traits of the Mediterranean framework application

Plant	Functions	Traits*
Ficus carica	Produce woody biomass Catch nutrients Catch deep water Produce marketable crop Cover soil	Fast growing Re-shooting capacity Deep rooting Rustic Drought resistant Bears marketable fruit
Populus spp.	Produce woody biomass Catch nutrients Catch deep water Cover soil	Fast growing Re-shooting capacity
Triticum spp.	Produce marketable crop Produce herbaceous biomass Manage soil structure Prevent nutrient loss Manage weeds	Fasciculate roots Bears marketable seeds Annual cycle Nutrient demanding
Vicia faba	Input nutrient Produce marketable crop Produce herbaceous biomass Cover soil Pollinate crops	N-fixing Bears marketable legumes Annual cycle Floral resources for pollinators
Medicago sativa	Input nutrient Produce herbaceous biomass Cover soil Pollinate crops Manage soil structure Catch deep water Manage weeds	N-fixing Annual cycle Floral resources for pollinators Deep rooting (up to 15m)
Punica granatum	Produce marketable fruit Pollinate crops	Bear marketable fruit Flowers visited by pollinators
Solanum lycopersicum	Produce marketable fruit Pollinate crops	Bear marketable fruit Flowers visited by pollinators
Cucumis melo	Produce marketable fruit Pollinate crops	Bear marketable fruit Flowers visited by pollinators
Lactuca sativa	Produce marketable leaves	Bears marketable product Shade tolerant
Rosmarinus officinalis	Produce marketable crop Pollinate crops Manage pests	Bears marketable leaves Produces aromatic compounds that repel pests Produce pollen early in the year Perennial
Salvia spp.	Produce marketable crop Pollinate crops Manage pests	Bears marketable leaves Produces aromatic compounds Hosts beneficial insects Flowers visited by pollinators Perennial
Olea europaea	Produce marketable fruit Produce marketable wood	Bears marketable fruit Rustic Slow growth
Cynara cardunculus	Produce marketable flower Pollinate crops	Bears marketable flower Flowers attract pollinators Perennial

*Sources: personal and expert knowledge; www.britannica.com; www.pfaf.org; www.actaplantarum.org

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