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An optimization model for the planning of multi-species agroecosystems: trading off economic feasibility and biodiversity

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Abstract

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Keywords

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1. Introduction

The integration of ecosystem production and conservation in agriculture is key in the sustainable development context, from both an ecological and a long-term economic perspective (Fischer et al., 2006). Agriculture pursuing the mere maximization of short-term productivity and income led in the past to the intensification of agricultural operations (Matson, 1997; Tilman et al., 2001; Godfray et al., 2010; Bonsch et al., 2015) and to the consequent loss of some major ecosystem functions (Power, 2010). Limiting adverse environmental impacts, maintaining multiple ecosystem services, providing adequate and stable socio-economic returns, and contributing to the restoration of habitats or ecosystem functions have emerged as essential features of the modern agricultural practices (Robertson and Swinton, 2005; Maeda, 2013; Gaba et al., 2015; Donia et al., 2017). Besides the simultaneous inclusion of these diverse and often conflicting objectives, the design of sustainable agro-ecosystems is also challenged by the presence of several interacting components and biophysical processes. Therefore, under a methodological perspective, integrated and system approaches are required to tackle this complexity (e.g., Matlock and Morgan, 2011). In this context, ecological engineering, defined as the study of "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1998), can effectively support the development of sustainable solutions based on ecosystem and engineering problem-solving approaches (Halbe et al., 2014; Mitsch and Jørgensen, 2004). Optimization approaches that integrate socio-economic with ecological and environmental needs or goals have become pivotal in the international commitments for sustainable agriculture (Hayashi, 2000; Pretty, 2008; De Groot et al., 2010; FAO, 2017; Barot et al., 2017). Optimization techniques should support the informed design of an agroecosystem, and allowing to consider both structural and the functional components of agroecosystems (e.g., species composition, soil, and water and nutrient cycles), as envisaged by the ecosystems services framework (De Groot et al., 2010) and the agroecological approach (FAO, 2014). In light of this need, the aim of this study is the development of a comprehensive optimization model to quantitatively support the planning of economically viable and diverse agroecosystems with informed decisions. To respond to this goal, we structured the paper in four main parts. In the first part, we analyze the decision process behind the planning of multi-species agricultural systems; secondly, we formulate the deriving optimization problem. As a third step, we apply the developed approach to a case study regarding the creation of agroecosystems aimed at the regeneration of deforested land in the Peruvian Amazon area. Finally, we discuss the obtained results, highlighting the main methodological challenges affecting the planning of multi-species agro-ecosystems.

2. A modelling framework for optimized planning of intercropped agroecosystems

2.1. Planning *diverse* agroecosystems

The capacity of agro-ecosystems to provide multiple services is key within the long-term sustainable development context. The maintenance of agrobiodiversity (FAO, 2004) has emerged as an essential aspect to pursue sustainable and multifunctional agriculture (De Groot et al., 2010; FAO, 2014; Barredo et al., 2015; FAO, 2016), under both an ecological and a socio-economic perspective. Firstly, ecosystem structure and composition are potential surrogates of natural processes to be replicated in manmade agroecosystems (Jackson and Piper, 1989; Ewel et al., 1991). Agrobiodiversity is, indeed, considered as an action lever to guarantee multiple ecosystem services (Altieri, 1999; Smit and Skinner, 2002; Tilman et al., 2002; Fischer et al., 2006; Doré et al., 2011; Ekström and Ekbom, 2011; Letourneau et al., 2011; Bommarco et al., 2013; Gaba et al., 2014; Bioversity International, 2016) and to improve resilience of agroecosystems (Elmqvist et al., 2003; Laliberté et al., 2010). Diversity can range from genes and species up to landscape scale (Gaba et al., 2015) and can cover many elements of an ecosystem such as the composition of populations, functional groups, and types of interactions which are essential to the supply of ecosystem services at the base of human well-being (Haines-Young and Potschin, 2010). Secondly, under a socio-economic perspective, agrobiodiversity has been proved to be an economically profitable synergy between conservation and production (Daily, 2001; Ricketts et al., 2004; Makate et al., 2016), and, despite it conflicts with immediate economic return (Guariso and Recanati, 2016), an effective strategy adopted to minimize income fluctuations (Lema and Majule, 2007; Mahoo et al., 2007; Antwi-Agyei et al., 2014). In particular, smallholder farmers in developing countries that wish both to maximize income and to avoid income fluctuations (Libbin et al., 2004), can (and in many cases do) cultivate a diversified selection of crops avoid to be caught into the so-called *poverty trap* (i.e., when poverty due to a bad yield persists and cannot be recovered without external interventions) (Azariadis and Stachurski, 2005).

Diverse agroecosystems deriving from mixed intercropping approaches (Vandermeer, 1989) thus represent effective solutions towards a more sustainable agriculture. These man-planted systems replicate many characteristics of natural forests, like the simultaneous presence of two or more plants species cultivated in the same field (Ghaley et al., 2005), and a diversified and tree-dominated architectural structure. The resulting agroecosystems can be classified within different agricultural system categories, ranging from agroforestry to analog forestry (Senanayake and Jack, 1998) (Figure 1). Successful mixed intercropping systems are widely implemented around the world (Brooker et al., 2015), even in most complex configurations like analog forestry (Kusters and Lammers, 2013).

Designing mixed intercropped ecosystems able to guarantee both environmental and socio-economic benefits conceptually represents a complex decision process. Comprehensive approaches considering the classical three-domain framework of sustainability (i.e., economy, environment, and society (Brundtland, 1987)) should be adopted to support farmers' plant choices in the planning phase. In this study, we address this issue by formulating an optimization framework aimed at supporting the design of sustainable agroecosystems based on mixed intercropping. In particular, it allows to investigate possible synergies and tradeoffs between environmental and socio-economic objectives, and the assessment of their evolution over time, with a focus on the first years of transient. In other words, the optimization model we developed attempts to respond to the following questions: Which combination of species guarantees the highest annual income? Do high agrobiodiversity rates cause strong losses of economic income? What about seasonal income variability, how severe is the conflict with the other two objectives? How tradeoff solutions look like?

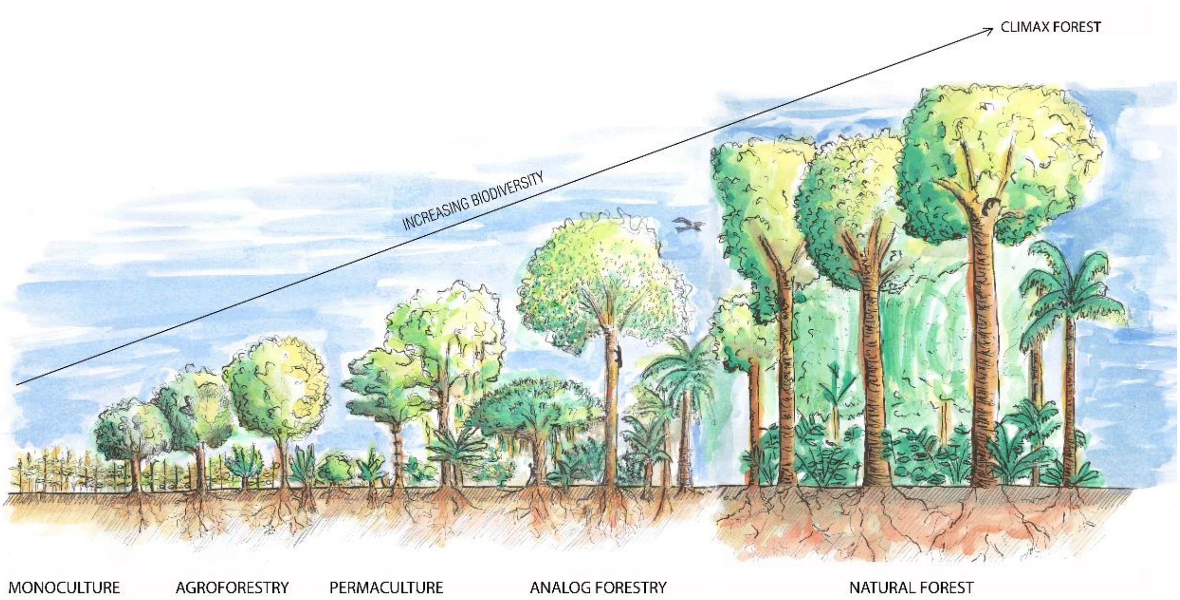

Figure 1. Existing agricultural production models, from monoculture to analog forestry. The ecological structure and species composition of analog forestry is close to that of natural forest (IAFN, www.analogforestry.com)

2.2. Model requirement and assumptions

The output of the proposed optimization problem is the mix of plant species for a given agricultural area (i.e., number of individuals for each considered species). The model is fed with data about suitable plant species that can potentially be cultivated in a given territory, with complementary information about their life cycle, growth, land occupation, productivity, and related economic performance. These are required by the model to simulate the evolution of the designed agroecosystem along the selected time horizon. In particular, for each of the considered species s, $s=\{1,\ldots,N\}$, the following information are required:

- the growth function $g_s(m)$ of the plant crown (m^2) along time, where m represents the number of months since planting;
- the replacement time R_s, which represents the number of months (from planting) after which trees of species s are uprooted;
- the minimum land requirement l_s, i.e., the soil surface needed by each individual of species s. Since we are dealing with agroecosystems characterized by vertical heterogeneity (composed of species with different heights), we group the selected species into two classes, according to their maximum height (in meter) and their behavior towards light, namely (i) shaded or lower species that can tolerate partial shading caused by highest species, (ii) shade canopy or shading species that are characterized by major heights, which includes species above 20 meters (Bieng et al 2014). For species in the shaded layer, l_s coincides with the crown extension at maturity, for higher and shading trees it represents a small area around the stem that cannot be covered by other species.

- the average profitability $p_s(g_s(m))$ of species s (currency/m^2). We assume that the harvest depends on the plant size through a function that is species-dependent and profitability is the product of the yield per unit of area (kg/m^2), and of the price per unit of yield (currency/kg) (see Supplementary Materials, Table S.2). From the agricultural viewpoint, this is the most critical assumption: it is indeed possible that the yield of each crop, when intercropping is adopted, will be influenced by the presence of other species. This effect may, in general, be positive (higher yield) or negative, but certainly data about all the potential crop combinations will not be available for many years in the future. For this reason, we assume a yield equal to the one of mono-cropping if the optimal cropping and environmental conditions (space, light, water, and nutrients) are preserved;
- the above assumption must be translated into a set of constraints that guarantee adequate resources for each individual of each species. For instance, competition for light may be taken into account through the maximum admissible shadow tolerance s_s, which represents the maximum fraction of the plant crown that can be shaded by higher trees. Therefore, we hypothesize that the species can growth undisturbed below this threshold (e.g., as in monocultures).

Once the species database is created, at least three objectives should be considered (Sumpsi et al., 1997), one for each pillar of sustainability (Brundtland, 1987). As for the economic sphere, the objective may be represented by the standard net present value of the revenue (currency·year^{-1}) from the agricultural production obtained from the considered area over the considered planning horizon. Under an environmental viewpoint, we can select agrobiodiversity as a structural and compositional proxy for sustainable and multifunctional agroecosystems. In this work, we will focus on the diversity at field and farm level because it directly depends on farmer's choice and it influences the generation and the delivery of many vital ecosystem services for rural activities (Mendenhall et al., 2016). Such on-farm biodiversity should be preserved through human intervention because it continues to evolve in response to natural selection, and is susceptible to threats such as disease, conflict and changing climate, land use and farmers' choices (Bioversity International, 2016). Diversity can be measured in terms of portions of available area occupied by each species. Given that, since the crop mix changes along the planning horizon, we will assume a yearly average value as a measure of plant diversity. Finally, the stability of economic income obtained from the agroecosystem can be chosen to assess the social dimension. It is a common objective among farmers (Hayashi, 2000; Ostrom, 2009), who are, indeed, risk averse (Quaas et al., 2007; Müller et al., 2011; Quaas and Baumgärtner, 2012) and thus try to reduce income fluctuations, or, equivalently, ensure a minimum income with a sufficiently high probability. Here we will consider the minimization of the variance of the monthly income as a representation of the farmers' desire of economic stability and thus of social acceptability of the overall plan.

It is important to underline that the agricultural scheme we aim at is quite different from a traditional cultivation plan (Haneveld and Stegeman, 2005): it will span over several years with crops sawn at the beginning together with small trees, which may afterward be replaced by different crops, to best follow the evolution of the whole ecosystem. In the same way, production patterns may change over time and the overall plan can thus be evaluated only looking at a horizon of several years.

2.3. Formulation of the optimization problem

Decision variables and agroecosystem evolution

The decision variables $z_{s,\tau} \in Z$ of the problem represent the number of plants (integer) of species *s*, planted in the τ-th month of the horizon *H*. The plant community is selected at each time step *t* (e.g., month) within the considered planning horizon (*H*). Assuming for instance 30 possible species and a horizon of 15 years, the total number of variables would be 5400, but it strongly reduces if we assume that the feasible and actual decision (i.e., $z_{s,\tau}$) may differ from zero only at the beginning of the agricultural season (e.g., year or semester). Moreover, an individual remains in the field until its age (t–τ, where τ is the month in which the tree is planted and *t* is the current time step) equals its replacement time R_s; afterwards it is uprooted and substituted by individuals of the same or of a different species. Given that, the total number of individuals of species *s* at each time step *t* ($z_s(t)$) includes both the survivors up to *t*, and the newly planted at *t*. This means that the population $z_s(t)$ is:

(1) $$z_s(t) = \sum_{\tau=t-R_s}^{t} z_{s\tau}$$

Each decision variable has obviously a non-negativity lower bound:

(2) $$z_{s\tau} \geq 0 \qquad \forall s, \tau$$

We assume that two main resources influence the species abundance in the field. The first is the availability of sunlight and concerns the crown dimension and evolution, while the second is the availability of soil. Similar constraints may be added to ensure the balance of nutrients and/or water.

The area occupied by the crown of each individual varies over time according to a function describing the growth dynamics. There exist different types of functions (e.g., logistic, Richards, Gompertz and Weibull; see Paine et al., 2012) that can be used to simulate the plant growth from one time step to another. They can be divided into two main groups: those that assume an asymptotic final size and those that do not. The selection of the growth function can change from a case study to another and should include all possible information related to the specific setting.

Objective functions:

The complete objective function consists in three components that should be simultaneously optimized: the maximization of economic income and agrobiodiversity, and the minimization of intra-annual income variability. As previously explained (Section 2.1), we aim to investigate possible conflicts and synergies between the these three criteria selected for the agroecosystem design. The first economic objective, i.e., the maximization of the net present value of the agroecosystem averaged over a horizon of *H* months (J_{eco}), can be written as:

(3) $$\max_z J_{eco} = \max_z \frac{1}{H} \sum_{s=1}^{N} \sum_{t=1}^{H} \sum_{\tau=t-R_s}^{t} \left[\frac{p_s(g_s(t-\tau))}{(1+r)^t} z_{s\tau} g_s(\tau) \right]$$

Where $p_s/(1+r)^t$ represents the discounted revenue (r being the discount factor, assumed equal to 0.05 in the following study) obtainable from each species per unit of area (m^2). Once $g_s(t)$ is defined, the revenue function can be rewritten as a function of time, taking into account when the first production (FP_s) and the replacement occur. It is thus defined as:

(4)
$$p_s(t-\tau)=\begin{cases}0 \ \text{ if } \ t-\tau\le FP_s \ \text{ or } \ m\ne m_s^* \\ k_s \ \text{ if } \ FP_s\le t-\tau\le R_s \ \text{ and } \ m=m_s^*\end{cases}$$

Where k_s is the income per unit of (crown) area (currency·m^{-2}) obtained from each *producing* species in the month m_s* of fructification.

The second objective is crop diversity. Different indicators are used to assess (alpha) biodiversity (Magurran, 1988), among which we selected Simpson diversity index calculated on the areal fraction. The deriving objective is defined by maximizing the average value of such an index along the horizon H (J_{div}):

(5)
$$\max_z J_{div}=\max_z\frac{1}{H}\sum_{t=1}^{H}\left(1-\sum_{s=1}^{N}\left(\frac{\sum_{\tau=t-R_s}^{t} z_{s\tau}g_s(t-\tau)}{A_{TOT}(t)}\right)^2\right)$$

Where $\sum_{\tau=t-R_s}^{t} z_{s\tau}g_s(t-\tau)$ is the area occupied by the individuals belonging to s at time t and $A_{TOT}(t)$ is the total area available, which is the sum of the agricultural area and the shaded area created by the shading species. More precisely,

(6)
$$A_{TOT}(t)=\sum_{s=1}^{N}\sum_{\tau=t-R_s}^{t} g_s(t-\tau)z_{s\tau}$$

is thus larger than the effectively available agricultural area A (i.e., field area) and changes in time depending on the growth of the crowns of the higher plants.

The last aspect under investigation is the social impact of intra-annual variability of farmers' income that can be expressed as the mean variance of the monthly net income obtained along the time horizon H:

(7)
$$\min_z J_{\text{var}}=\min_z\frac{1}{H}\sum_{t=1}^{H}\left(I(t)-I_{AVG}\right)^2$$

Where the monthly net income $I(t)$ is obtained by summing the product of unit revenue from each species and the area occupied at time t, and I_{AVG} is the average value of such a variable. More precisely, $I(t)$ can be written as:

(8)

$$I(t)=\sum_{s=1}^{N}\sum_{\tau=t-R_s}^{t}p_s(t-\tau)z_{s\tau}g_s(t-\tau)$$

Constraints

The constraints of the problem may refer both to the availability of local resources and to the specific demand of the (local) market that can determine some limits to the selection of the plant mix. We will consider here only three constraints due to the availability of area:

- available agricultural soil surface *A*:

(9)

$$\sum_{s=1}^{N}z_s(t)l_s\leq A \quad \forall t$$

where $z_s(t)$ is as previously and l_s is their minimum land requirement.

- availability of area that is directly irradiated by sunlight, defined as:

(10)

$$\sum_{s=1}^{N}\sum_{\tau=t-R_s}^{t}(1-s_s)g_s(t-\tau)z_{s\tau}\leq A \quad \forall t$$

- and finally, the compatibility of the shaded area with plant tolerance:

(11)

$$\sum_{s\in shading}\sum_{\tau=t-R_s}^{t}g_s(t-\tau)z_{s\tau}\leq\sum_{s\in shaded}\sum_{\tau=t-R_s}^{t}s_sg_s(t-\tau)z_{s\tau} \quad \forall t$$

which means that the shadow produced by the higher trees is smaller than that can be tolerated by lower plants.

Optimization settings:

Adopting the classical constraints method, it is possible to create the sets of Pareto efficient agroecosystem plans according to the three selected objectives. Even considering the integrality constraint (which may indeed be relevant for the larger trees), the overall complexity of the problem remains limited and allows a rather quick solution whatever integer programming software is used. For instance, for the following case study we adopted What's best! 14.0 software by LINDO^{TM}, selecting the Integer solver (Branch-and-Bound) with default computation options except for integrality (absolute one set equal to 0.001 and relative one set equal to 0.008) and relative optimality (set equal to 0.05). Each point of the Pareto set required solution times of the order of tens of seconds on an Intel Core I7 pc with 4 processors and 4.00 GB RAM.

3. Case study: intercropping for the regeneration of deforested areas

The ongoing deforestation in the Amazon basin is causing a huge loss of natural ecosystems characterized by the highest biodiversity rates in the world (Edwards, 2016; Fearnside, 2005; Gibson et al., 2011). The deforested and degraded lands can be turned into a sustainable resource for the region if their regeneration and management follow agroecological approaches, like mixed intercropping. We selected this case study as a demonstrative application due to the importance of biodiversity in the area and the fundamental role of local communities, whose adequate socio-economic conditions can potentially benefit from this regeneration process. In particular, we focus on the Peruvian Amazon, and on Madre de Dios region located about 800 km east of the capital Lima, close to the borders with Brazil and Bolivia. In this area, deforestation due to agriculture and mining activities is destroying one of the precious biodiversity hotspots in the world (www.conservation.org). The first fundamental step of the selection of suitable plant species has been performed by local associations, Arbio Peru (www.arbioperu.org), Simbio (www.simbio.life), and CATIE (www.catie.ac.cr). As part of the project FIDECOM - Innòvate Peru, they selected a set of 30 productive species (see Table S.2 in the Supplementary Materials and Figure 4 for a complete list) among the thousands of plant species present in the Peruvian Amazon (www.siamazonia.org.pe). The species are all suitable cultivars for the region, provide different types of products (e.g., food and medicinal herbs) and can tolerate different critical environmental conditions (e.g., flood or drought). Data about plant species life cycle (e.g., time of first production, replacement time), morphology (height and crown area), and profitability (PEN m^{-2}, with PEN being Peruvian Nuevo Sol, and 1 PEN being about 0,3$ US) have been collected from existing literature and public database (major sources are www.infoagro.com, tropical.theferns.info, sistemas.minag.gob.pe, www.agricultura.gob.do and siea.minag.gob.pe), and from the consultation with local farmers in the area (see Supplementary Materials, Table S.1 and Table S.2).

Beyond the data used, the following assumptions have been adopted to analyze this specific case study:

- the effective time of plant selection occurs at beginning of the agricultural season, which corresponds to the beginning of the year;
- the time horizon analyzed is 15 years;
- plant growth is modelled through the beta function (12) defined by Yin et al. (2003). It is characterized by proper flexibility to describe asymmetrical sigmoid patterns, it belongs to the asymptotic family and thus is suitable to analyze problems that include the entire lifespan (Paine et al., 2012). It is formulated as follow:

$$g_s(t-\tau) = g_s^{\max}\left(1+\frac{M_s-(t-\tau)}{M_s-t_{m,s}}\right)\left(\frac{t-\tau}{M_s}\right)^{\frac{M_s}{M_s-t_{m,s}}} \qquad (12)$$

where:

- $t_{m,s}$ is the time at which maximum growth rate is obtained;
- g_s^{max} is the maximum value of crown area, which is achieved at M_s (maturation time, assumed equal to the time of first production).

For the sake of simplicity, from the obtained Pareto front we focus on four main solutions (the best solution for each one of the considered objectives and a trade-off solution) to analyze the evolution of the objectives and composition of the obtained agroecosystems over the considered time horizon. As a last step, we test the sensitivity of the obtained agroecosystems to the variation of some model inputs. In particular, we consider possible variability of profitability per unit of area (PEN m^{-2}), which includes both productivity and price variation, basing on the time series supplied by the Peruvian government (sistemas.minag.gob.pe). We first perform the so-called one-at-a-time sensitivity analysis (OFAT or OAT, Pianosi et al., 2016) on the profitability (PEN m^{-2}) of each selected species. Secondly, we test how the agroecosystem performance and composition change by varying all the inputs (values of profitability) simultaneously, by randomly extracting them from their historical distributions (siea.minag.gob.pe).

4. Results

The obtained Pareto front is represented in Figure 2 through its projections on the intersection planes between each pair of objectives (i.e., axes). In particular, in each 2-D plot (i.e., intersection of each pair of axes), the blue solid curve represents the Pareto-efficient solutions included in the projection on the J_{eco} - J_{div} plane, while the green dashed front includes those belonging to the projection on the J_{eco} - J_{var} plane. We reported only these two intersections involving the economic objective, because its exclusion (i.e., just looking at species diversity and income variance) has no meaning in agricultural contexts (i.e., minimizing J_{var} towards zero, would led to no plantation to obtain, while maximizing J_{div} would led to uniformly partitioning the available area among the available species). For the sake of completeness, we show both frontiers also on the plane J_{div}-J_{var} (Figure 2 c). The blue diamond marker represents the so-called Utopia point, i.e., what can be achieved by optimizing each objective separately. Empty dots represent the best alternatives for each objective (i.e., J_{eco}*, J_{div}*, J_{var}*), while the red squared marker is the tradeoff solution (T-O*) found through the criterion of minimum distance from the utopia point when the objectives are equally weighted. In Table 1, we summarized the performances of abovementioned solutions.

Table 1. Performances of the best solutions for each of the three considered objectives (J_{eco}*, J_{div}*, J_{var}*), the suggested tradeoff solution (T-O*) and the Utopia point.

Solution	J_{eco}	J_{div}	J_{var}
	Mil PEN $year^{-1}$ ha^{-1}	/	(Mil PEN $month^{-1}$ $ha^{-1})^2$
J_{eco}*	9.05	0.44	2.29
J_{div}*	3.58	0.97	0.028
J_{var}*	7.82	0.49	0.001
T-O*	7.72	0.85	0.287
Utopia	9.05	0.97	0.001

From Figure 2 (a) and (b), it emerges a clear conflict between economic income and both crop diversity and income variability. The willingness to have a high number of species in the agroecosystem results in a stronger reduction of the income objective (- 60% with respect to J_{eco}*) with respect to that of economic variability (-13.5% with respect to J_{eco}*). If we compare species diversity and income variance (Figure 2 c), we find that, despite an initial synergy, within the variance range between 2 and 0.6 (Mil PEN $month^{-1}$ $ha^{-1})^2$, the two objectives come up to be conflictual. This is due to the fact that a mix of few species that have continuous production along the year can reduce the intra-annual income variability, but, in the end, an extreme minimization of the income variance (J_{var}*) causes a reduction of about 50% with respect to the highest diversification J_{div}*.

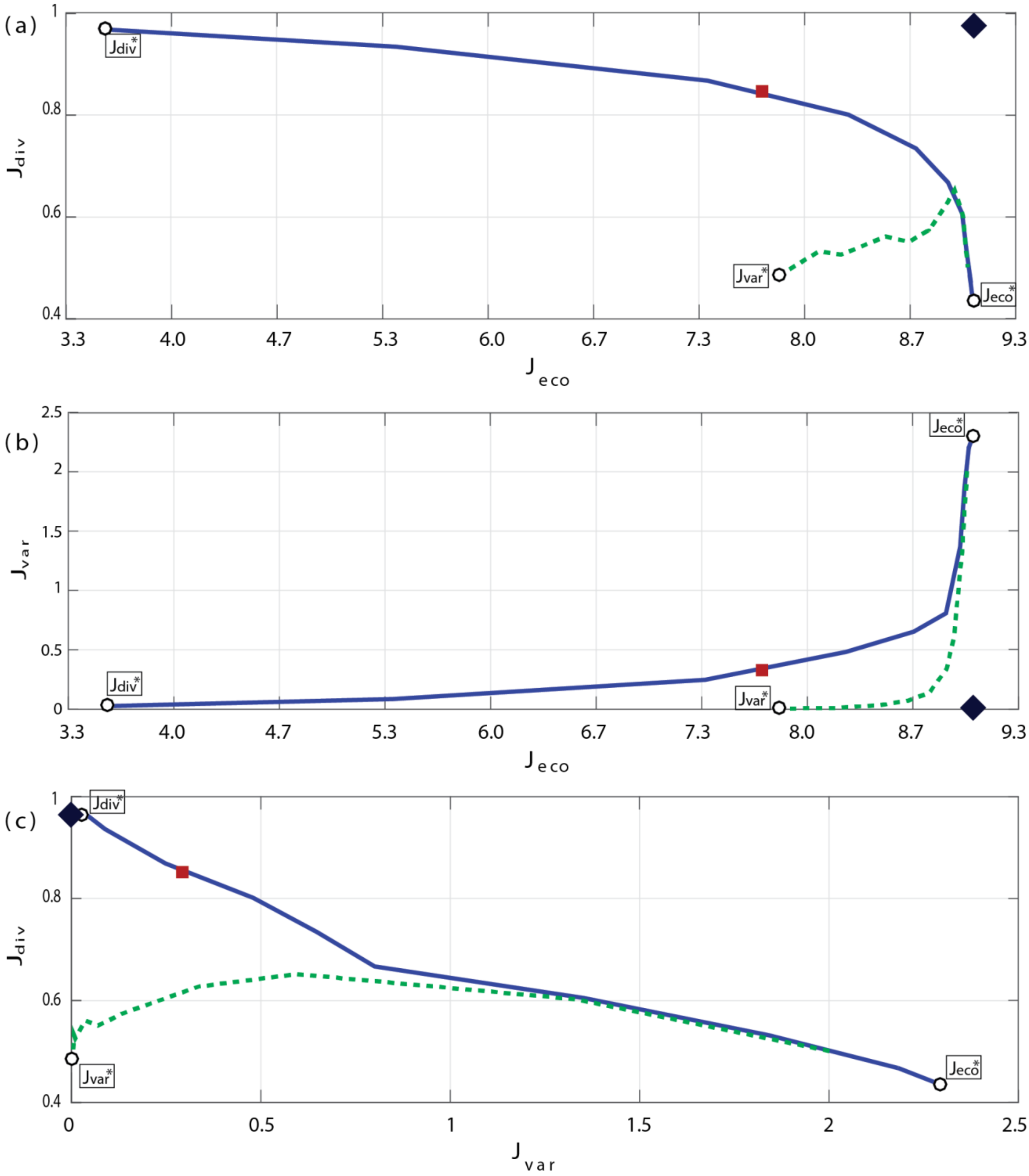

Figure 2. Sections of the 3-D Pareto front of efficient plans: (a) shows the plane J_{eco} and J_{div}, (b) the plane J_{eco} and J_{var}, and (c) the plane J_{var} and J_{div}. The blue diamond is the Utopia point, the empty dots are the best solutions for the three considered objectives and the red square is the tradeoff solution at minimum distance from the Utopia point.

As explained in the introduction, these complex agroecosystems usually have an initial transient during which perennial species are growing, and fast-growing species are planted to maximize the soil cover. To analyze this crucial phase, we evaluated the evolution of the three indicators along the 15-years horizon (Figure 3). The first graph shows the evolution of annual income. The alternative that guarantees the maximum annual income (J_{eco}*) stabilizes at 18 Mil PEN year^{-1} ha^{-1} after 7 years. Other solutions, after the initial transient, during which the majority of them performs even better than the best-income one, show oscillatory behaviors along years, caused by plant dynamics and life cycles. Crop diversity index achieves stable values in all the alternatives after 7 years. Concerning the best income solution (J_{eco}*), the index is relatively higher in the first years thanks to the presence of several fast-growing species. Finally, also intra-annual variability achieves stable values after 7 years. In particular, in the first years, all the alternatives have lower values of the variance due to the large presence of fast growing species that produce along the whole year (e.g., *ojito de pescado*). When those species are reduced or removed (because generally characterized by lower economic values), the values of variance increases.

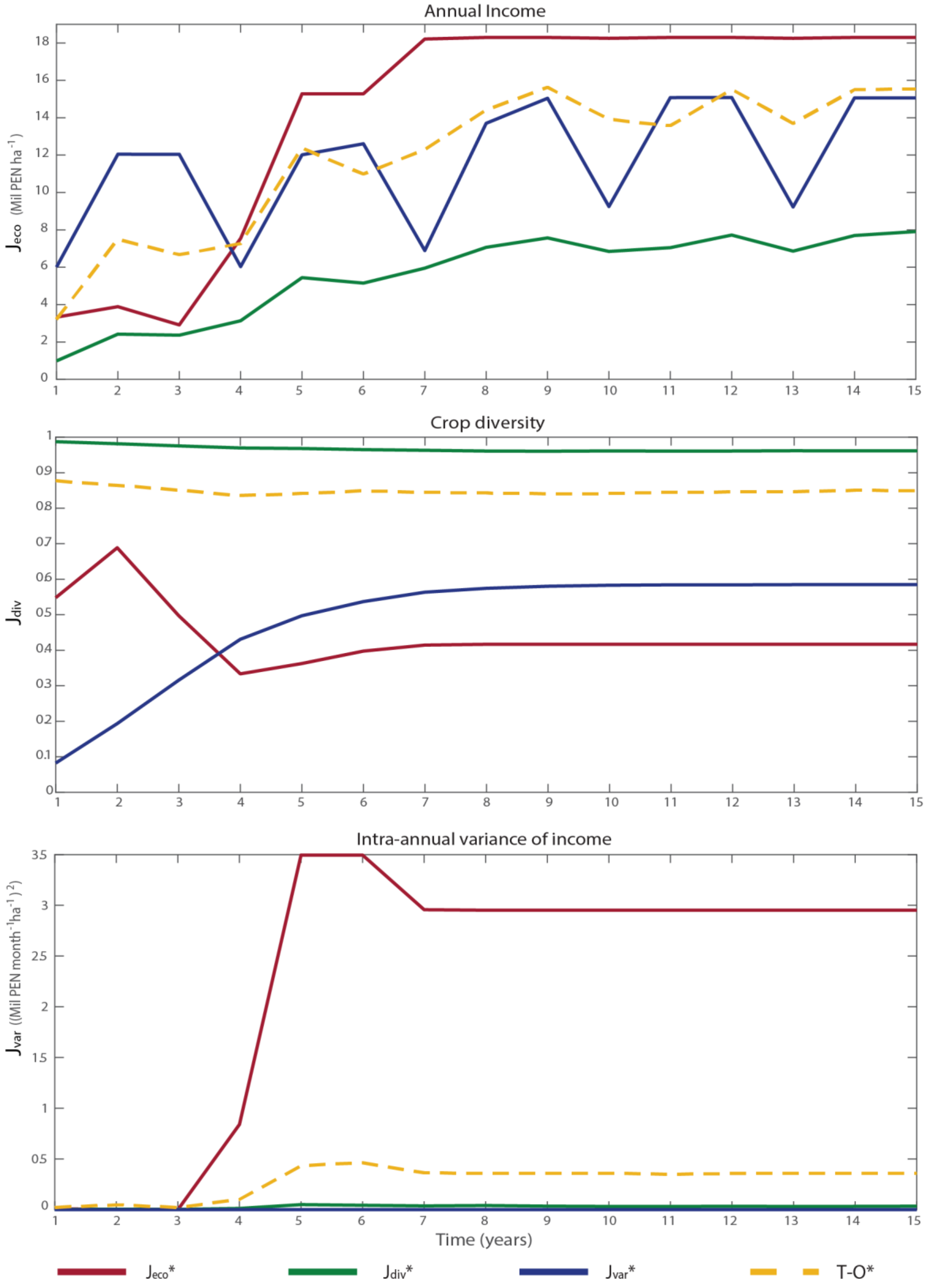

Figure 3. Stepcosts values along 15 years of the best solutions for each objective (J_{eco}*, J_{div}*, and J_{var}*) and the best tradeoff solution (T-O*) determined through the criterion of minimum distance from the utopia point.

The above-described evolution patterns are confirmed by the area charts reported in Figure 4, which show the distribution of the area among the different selected plant species. Again, each subplot corresponds to a Pareto-efficient solutions (points J_{eco}*, J_{div}*, J_{var}*, and T-O* in Figure 2). Maximizing the biodiversity (J_{div}*) clearly guarantees both a high number of species and a more homogeneous distribution of the available area among selected species. Conversely, the minimum intra-annual income variance is obtained with a relatively small mix of species, since the highest portion of area is dedicated to those species that guarantee continuous production along the year (e.g., *ojito de pescado*, *aguaje*, and *coco*).

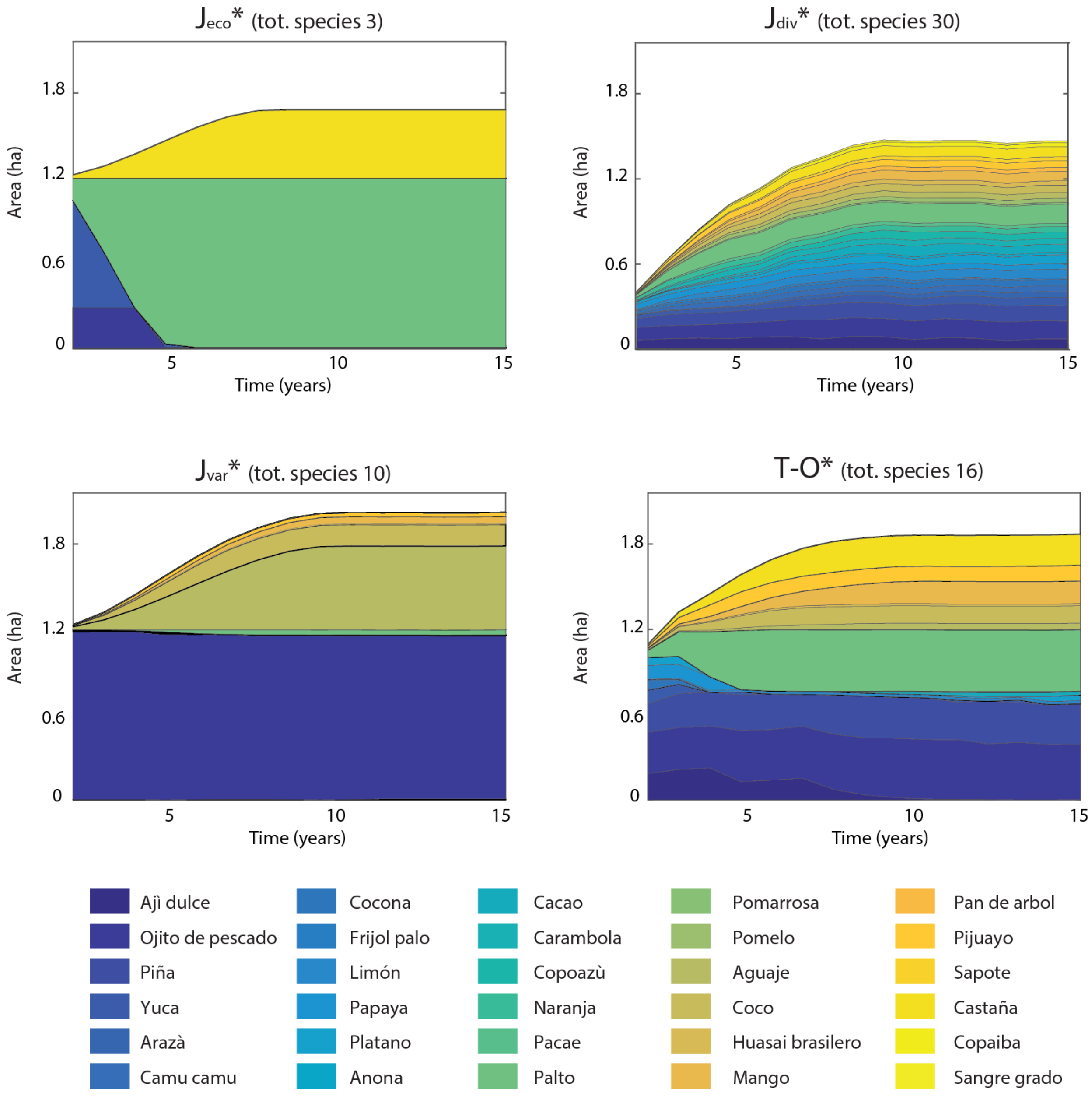

Figure 4. Area chart of Pareto-efficient agroecosystems: best alternative for each objective (J_{eco}*, J_{div}* and J_{var}*) and a tradeoff alternatives (T-O*). The number of species in brackets refers to those cultivated during the last year of the time horizon. The area reported in the chart represent the sum of all plant crowns, which evolves according to plant dynamics.

Besides the species diversity, we can assess the structural diversification of the obtained agroecosystems at the end of the time horizon. Taking inspiration from agroforestry practices (Schaefer, 2011), we created five species categories (i.e., strata or layers) defined according to the maximum height of plant species: up to 2 m stratum 1 (S1), 2-8 m stratum 2 (S2), 8-15 m stratum 3 (S3), 15-30 m stratum 4 (S4), above 30 m stratum 5 (S5). The solutions obtained (Figure 5) show that increasing the number of species can guarantee also a more diversified vertical structure, homogeneously distributed among the defined strata (J_{div}*, Figure 5, upper-right subplot).

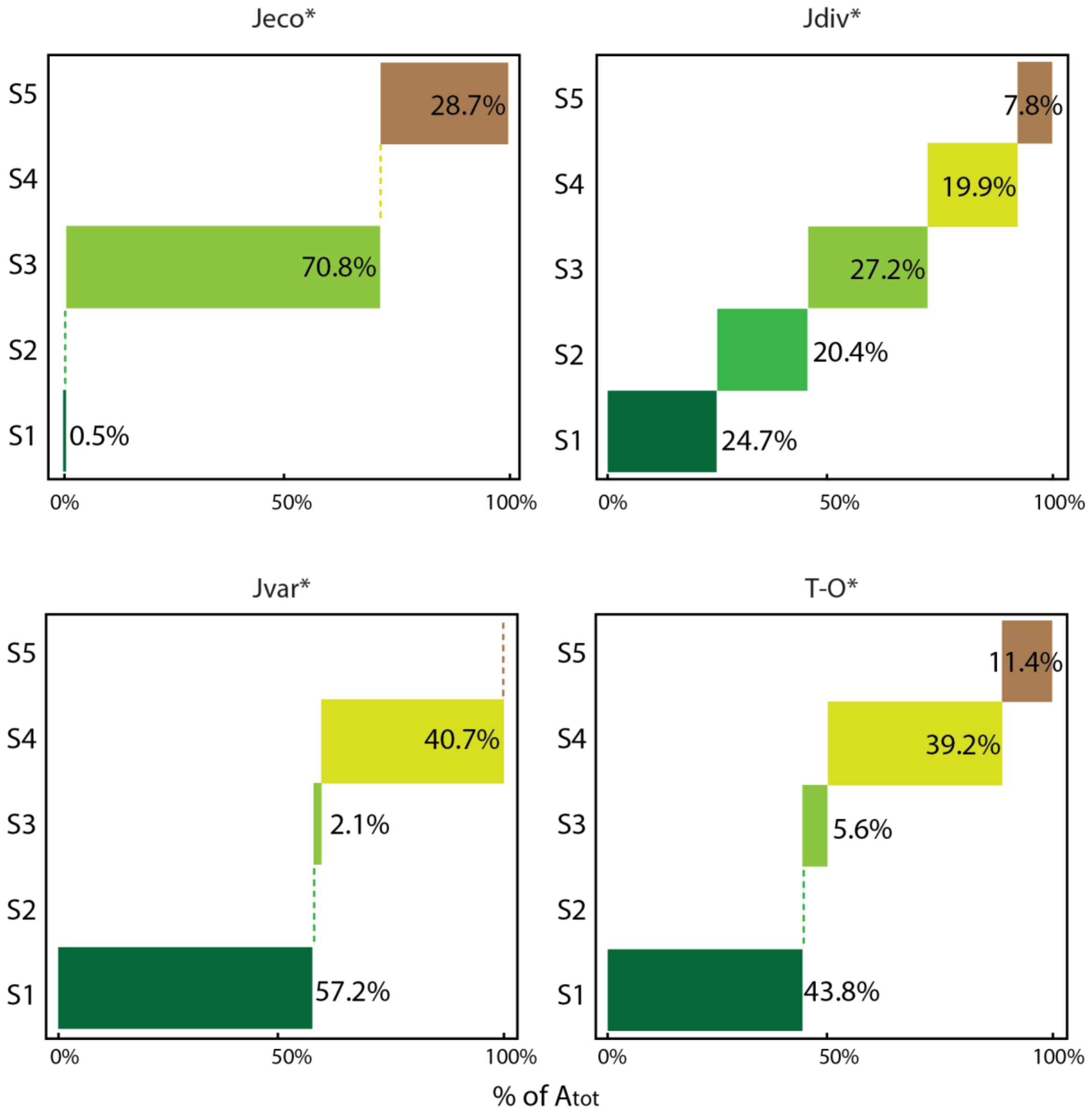

Figure 5. Optimal distributions of total area (A_{tot}) among plant species grouped into strata. On the x-axis we reported the percentage of areal occupation, while on the y-axis, we reported the defined five strata.

4.1. Sensitivity analysis

To test the robustness of the obtained solutions under the influence of variable future scenarios, we perform a sensitivity analysis over crop prices. As an example, we focus on the T-O* solution and we modify the value of profitability of each of the selected species, by lowering them down to their lowest historical value (see Table S.1 in the Supplementary materials). The entity of variation with respect to T-O* depends on the considered objectives: J_{eco} ranges from -0.82 (-7%) to + 0.22 (+1.9%) PEN m^{-2} $year^{-1}$, J_{div} ranges from -0.19 (-1.5%) to +0.02 (+0.1%), while J_{var} varies from –0.2 (-71%), to +0.07 (+24.4%) (PEN m^{-2} $year^{-1})^2$ (see Table S.3 in the Supplementary materials). Figure 6 shows the breakdown of the total area among the selected species at the 15th year. The first row reports the T-O* scenario, obtained by assuming average values of profitability for all the species. All the other rows are named with the species, whose profitability has been lowered to the historical minimum. Results show that, despite small variation, nine out of thirteen species are selected in any case (darker columns), and they occupy the majority of the available area (95.1% on average).

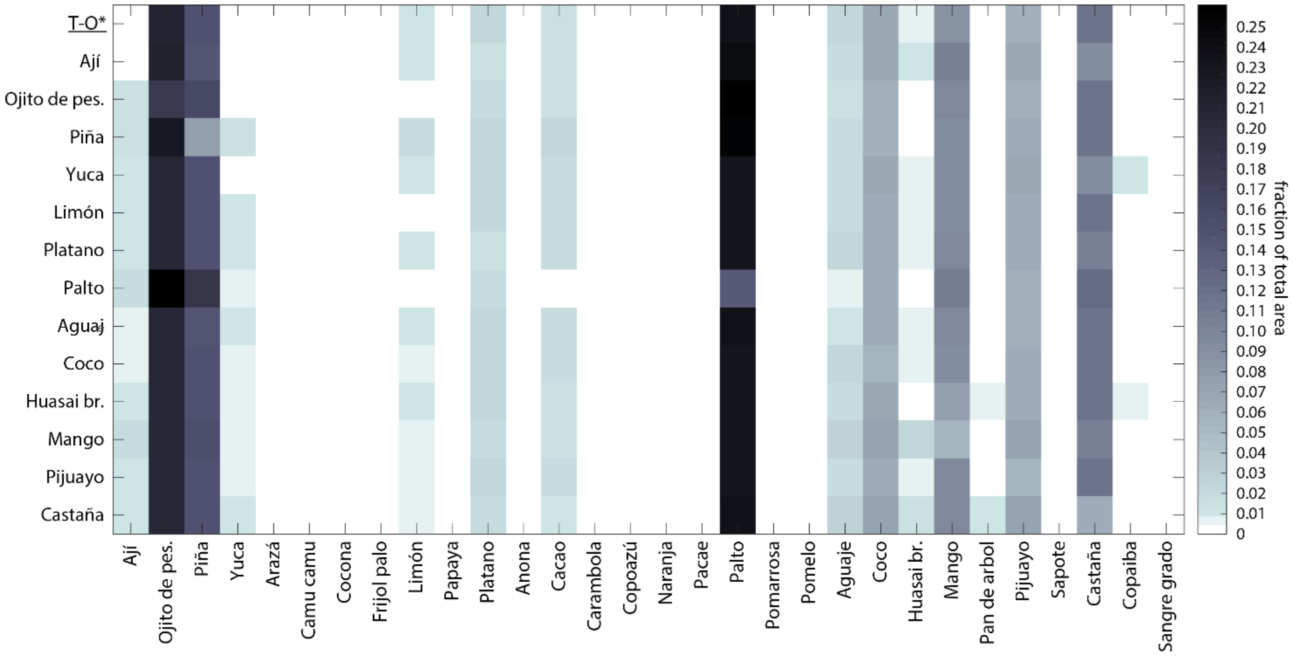

Figure 6. OAT sensitivity analysis on the profitability of species selected in T-O* solution. In the first line (from above), we report the area breakdown among the considered species (x-axis) related to solution T-O*. Each following line represent single steps of the OAT sensitivity analysis, in which the values of profitability of the species reported in the label is reduced to its historical minimum.

We perform a second sensitivity analysis by simultaneously changing all the values of species profitability (i.e., random extraction from historical distribution, 100 runs). The thirteen species included in T-O* are selected in all case (in Figure 7, the related boxes range within positive values of areal fractions), even if by occupying different fractions of the area (in Figure 7, values of occupied area range around the median, which is represented by the red dash). Few others (i.e., *Aji*, *Yuca*, *Copoazù*, and *Pan de arbol*) are introduced in some cases, while the remaining thirteen are never chosen. Regarding the objectives, they vary on average between +2% (J_{eco}) and 19% (J_{var}) (see Supplementary Material, Table S.4).

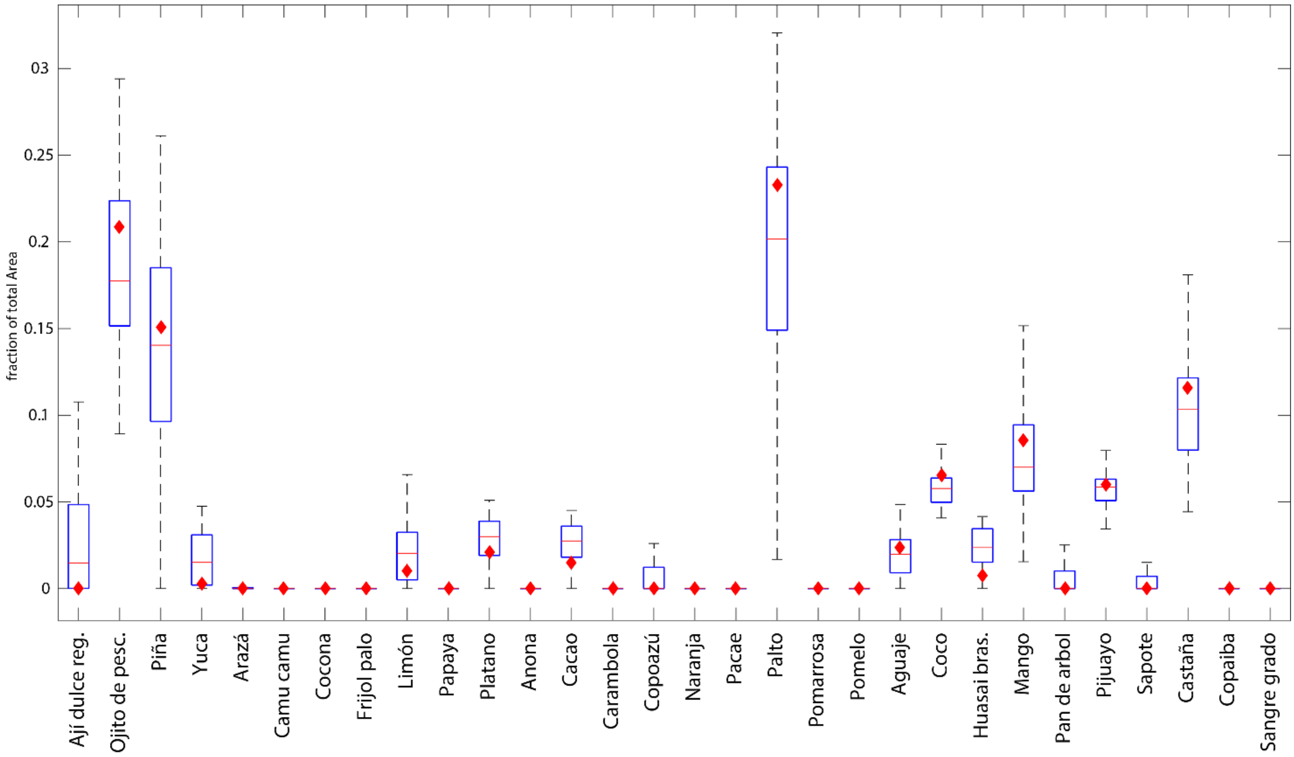

Figure 7. Sensitivity analysis obtained by simultaneously changing all the values of profitability (PEN m^{-2}). The red diamond markers represent the T-O* solution. On each box, the central dash indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles of the results obtained in the 100 runs, respectively. The whiskers extend to the most extreme data points not considered outliers.

5. Discussion and conclusion

This study presents the formulation of an optimization model aimed to support decisions behind at the design of agroecosystems. The model is fed with data about plant morphology, life cycle, and profitability of suitable cultivars for a given territory and provides the planting schedule for each agricultural season along the considered planning horizon. The main peculiarities of the developed tool are (i) its comprehensiveness, since it incorporates the three pillars of sustainability into the objective to be optimized (i.e., average annual profitability, agrobiodiversity, and income variability), and (ii) the quantitative nature of the outcomes. These two elements allow to effectively and quantitatively support the design of sustainable agro-ecosystems. To show its applicability, we demonstrate the proposed optimization model onto the design of mixed intercropping systems aimed at the regeneration of deforested lands in the Peruvian Amazon. From the obtained results, we could assess the tradeoffs between the socio-economic and environmental objectives, with a focus on the first years of transient. A clear conflict between the economic perspective (i.e., maximization of annual income) and the maintenance of biodiversity has emerged. A high level of crop diversity causes an income decreases up to 60% (with respect to the highest achievable income). This highlights the need of institutions' support, at least in the short term, to compensate these losses while supporting biodiversity and multifunctional farming systems (in the long run, further investigation is needed to assess possible benefits, due to the reduction of input costs or to the higher resilience to climate changes). On the other hand, an important socio-economic criterion like the minimization of income fluctuations showed to be able to support, at least partially, an increment in the diversity of the obtained agroecosystem. The analysis allows to investigate the transient state of the designed agroecosystems (mainly based on perennial crops that take time to grow) in terms of evolution of the relative performances. The solutions always represent an evolving situation in the first years when higher trees are growing; their sunlight requirements is growing as well and their shadow is limited. For this reason, at the beginning, more valuable, but more sun demanding short rotation plants may be sown, while after some years, more shadow tolerant plants are selected. Furthermore, it emerges that the higher results obtained in the first years after planting do not correspond to the optimal long term conditions, which means that selection of the planning horizon plays a crucial role. It is necessary to point out that, in the long term, agroecosystems of the type considered here will not reach an equilibrium condition with the same area assigned to each species (i.e., the same products), since all plants are periodically uprooted and thus, even after the transient, the situation is continuously changing.

The developed optimization framework allows to capture the transient dynamics of the described ecosystems (i.e., ecological succession), estimate the related sustainability performances, and highlight eventual tradeoffs and synergies. Moreover, it allows to identify three main methodological challenges for the optimal design of mixed intercropped agroecosystems. The first regards the handling of evolving solutions in time and the consequent choice of planning horizon: which should be the time reference of our objective? When should it be assessed? Accurate models of the agroecosystem could support a deeper analysis of system dynamics and possible long-term conditions (e.g., periodicity and amplitude of the variation that would occur). The second challenge concerns the definition of proper objectives regarding the structure of the agroecosystem and the role of biodiversity and their link with ecosystem functioning. Is crop diversity a sufficient proxy to describe the “architecture” and the functioning of the ecosystem? In our case, species diversity turned out to well support at least a diversified vertical structure, but other aspects, like for instance nutrient balance, may also be relevant and should be further assessed to turn them into additional problem constraints. It is also interesting to note that some classical biodiversity indicators (e.g., Simpson index) are difficult to interpret in such evolving situations. They were in fact developed for some kind of static situation where the area used by each species or their abundance could be considered a good indicator of its presence. Some new type of indicator, i.e., objective functions that can capture the evolution of biodiversity over the years, is thus necessary especially in such complex and multifunctional agroecosystems. Thirdly, the competition for resources within the agroecosystem and future climate and economic scenarios will influence both the interactions among crops, their productivity and their profitability. Therefore, besides light and space considered in our example, also nutrient- and water-related conditions should be included. These latter, however, strongly depends on the area or the field under study, and may require much additional information and simulation models. In addition, the variability of future scenarios can also affect the performance of plant species in terms of productivity and the overall economic situation may change prices in a significant way. These are the reasons why, currently, an extensive sensitivity analysis is possibly the only way to test the robustness of the proposed planting schedule and thus support farmers’ decisions.

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Supplementary Material

Highlights

- Design of sustainable agroecosystems should be based on comprehensive methods
- We propose an optimization model integrating the dimensions of sustainability
- Economic benefits may conflict with socio-ecological ones
- Obtained agroecosystems evolve following ecological succession path
- Tradeoff analysis is key to promote the integration of conservation and production