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Planning Complex Agro-Ecosystems: The Case of Analog Forestry

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Abstract:
Traditional agroecosystems, aimed at maximizing the short term productivity, are characterized by oversimplification of ecological structure and dependence on the use of external inputs. Moreover, intensive agriculture is one of the main cause of deforestation. The main consequence of traditional agriculture is the loss of natural ecosystems and of their precious services. Analog forestry has emerged as a sustainable productive model able to be integrated in forest contexts, without degrading their ecological functions. The obtained agro-ecosystem is characterized by an ecological structure similar to the one of forest, and by the presence of several productive species in the same area. In this study we formalize a planning problem aimed at the optimized design of an analog forest on the medium term. In particular, besides the maximization of income, we considered both ecological (i.e., the presence of different vertical layers and several species) and socio-economic requirements (i.e., the smoothing of both inter- and intra-annual variability of income). We focus the analysis on the Peruvian Amazon, basing on a species database created by ArBio, a Peruvian association which promotes the analog forestry as tool for pursuing the conservation of forest ecosystem services. The obtained results show that the inter-annual income variability, characterizing an approach of short-term maximization, can be eliminated by adopting the gradual planting of individuals belonging to the same species. Secondly, we quantified the economic and ecological performance of the designed analog forest under different settings of the planning problem. The introduction of the defined ecological and socio-economic constraints affects the economic performance on the medium term, by reducing the annual economic income up to 80%.

Keywords*: Analog Forestry; Amazon; Sustainable agriculture; Biodiversity*

1. INTRODUCTION

Traditionally, agricultural areas are designed to maximize the short-term production and relative economic return. This usually means intensification of processes, structural simplification of the derived agro-ecosystem (i.e., monoculture), and degradation of important ecosystem services (e.g., regulating and supporting ones) in favor of product provision (Millennium Assessment Board, 2005). This becomes even more considerable when agricultural lands are created by converting natural ecosystems, like forests. Their transformation means loss of important ecosystem services, whose economic value has been estimated to be of the order of magnitude of trillions of US dollars per year (Costanza, 1998; Millennium Assessment Board, 2005; Costanza et al., 2014). Besides the economic value, in tropical contexts, the transformation of virgin forests into intensive agricultural assets consists in an irreversible process under an ecological point of view (Engel et al., 2015). Since intensive agriculture (e.g., monoculture, and cattle ranching, are among the main causes of deforestation (Hansen et al., 2016), in the last decades, less intensive and low-input agricultural productive models have been proposed and implemented. Analog forestry, or successional agroforestry, is a promising agro-ecosystem for tropical forest contexts. It is able to provide food and other marketable products on the medium-long term, while maintaining the ecological structure of forest, and therefore being supposed to maintain the ecological functions of the virgin ecosystem.

In order to guarantee these ecological services, the design of such complex agroecosystem should take into account ecological dimension together with the economic one (Mercer et al., 2014). Analog forests are characterized by specific structural elements (e.g., different vertical layers, from shrubs to higher trees), aim to eliminate external inputs (e.g., chemicals, water and energy) and guarantee a wide production over the whole year. Given the amount of requirements to be guaranteed and objectives to be pursued, the design of these complex agro-ecosystems need the support of optimization tools like mathematical programming and stochastic dynamic programming. These techniques are widely use for the optimized design of simpler agroecosystems, like agroforestry ones (Mercer et al., 2014).

In this study, we formulate a preliminary planning problem aimed at the optimized design of an agricultural area dedicated to analog forestry. We focus on the Peruvian Amazon context, in particular, on the Madre de Dios region, where the analog forestry has been preliminary introduced by ArBio (http://www.arbioperu.org/), a non-profit organization and one of the Peruvian partners of the International Analog Forestry Network (IAFN, www.analogforestry.com). Basing on a species database developed by ArBio, we investigate the evolution of annual income in the long terms and we asses both the economic and the ecological performance of this agroecosystem under different settings of the planning problem.

2. THE ANALOG FORESTRY AND ITS APPLICATION IN THE PERUVIAN AMAZON

The analog forestry is a particular method of agroforestry. It was originally developed in Sri Lanka for restoring productivity of degraded lands and providing new sources of food and income to local people. This agro-ecosystem imitates the original native forest and has *analogous* structure and ecological functions and, at the same time, it involves productive and marketable species. Differently to traditional intensive agricultural models, it does not use chemical fertilizers, herbicides, pesticides or heavy machinery, but creates compost, plant nurseries through proper combinations and successions of species.

The approach behind analog forestry is based on three main concepts (Senanayake and Jack, 1998):

- *Mimicking natural forests* (i.e., climax or sub-climax vegetation) in its architectural structures and ecological functions similar to the original (Figure 1);
- *Ecological succession* is adopted by analog forestry to create stable tree-dominated ecosystems. It is applied to the restoration of degraded land, and the cultivation process begins with early colonizer and sun-loving species, and then progresses to a more mature forest structure. From the first stages it provides valuable products.
- By implementing analog forestry, opportunities to enhance landscape biodiversity and connectivity, protect rivers or create biological corridors or buffer areas (*landscape ecology* elements) can be identified.

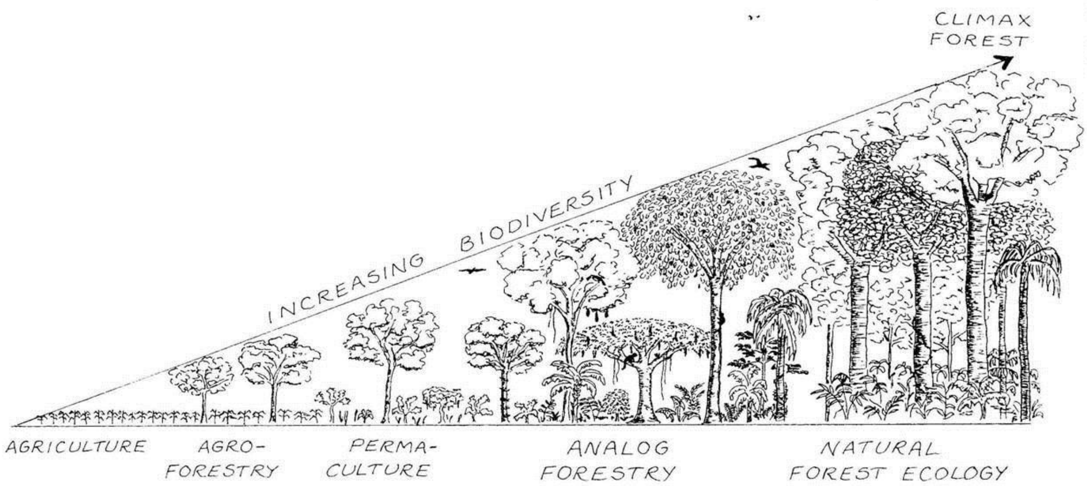

Figure 1. The ecological structure and species composition of analog forestry is close to the ones of natural forest (IAFN, www.analogforestry.com)

The derived agroecosystem guarantees the presence of both different vertical layers (i.e., from lower herbs to upper canopy) and several productive species in the same area. Successful analog forests are present in Sri Lanka, Burkina Faso, Costa Rica and 18 other countries around the world, especially in tropical areas (Kusters and Lammers, 2013).

The Amazon rainforest is experiencing high deforestation rates due to different human activities (Aguiar et al., 2012), among which agriculture plays a relevant role (Sombroek and Higuchi, 2009). Nowadays, Peru is characterized by a medium deforestation rate, but with an increasing trend of forest conversion due to smallholder agriculture, artisanal gold mining and industrial agriculture, mainly for palm oil (Hansen et al., 2016). This loss mainly affects the primary forest (Potapov et al., 2014). In the region of Madre de Dios (Figure 2) the deforestation process has been increasing especially since 2011 (Velarde et al., 2010; Terra-i, 2012), when the Peruvian path of the Inter-Oceanic highway was finished.

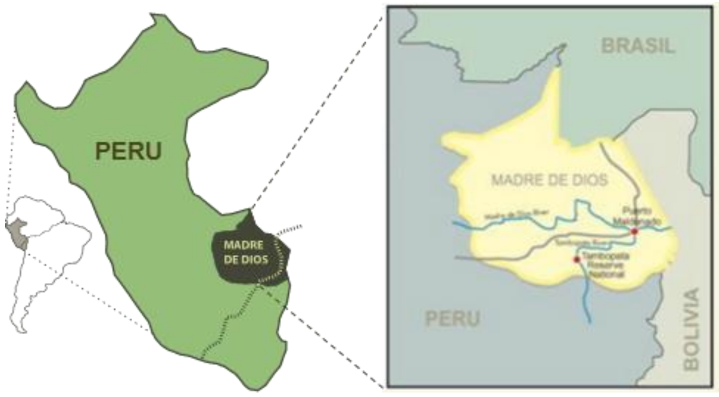

Figure 2. Area of study: the region of Madre de Dios located in the Peruvian Amazon

Given this context, alternative and sustainable economic activities, able to coexist with the virgin rainforest, are required. ArBio, an association which operates in the Peruvian region of Madre de Dios since 2010, promotes the conservation of the rainforest through different activities like absolute conservation, eco-tourism and analog forestry. The activities are implemented in the land concessions granted by the association, and aim at preserving the forest ecosystem and its functions on one hand, and supporting local communities, whose livelihoods, based on forest products, are characterized by intra-annual variability, due to seasonal activities (e.g., fruits gathering).

3. MATERIALS AND METHODS

3.1. Database of suitable species

The database used in this work was created by ArBio operators during the last year. It includes 30 species, which are compatible with the climate and soil characteristics of Madre de Dios, and are marketable in the Peruvian context. For each species, we collected information regarding average economic yield, production cycle (production months, time of first production and time of replacement), dimension and size (crown, height, trunk diameter), product function (food, medicinal, aromatic etc.), nutrients and tolerance to specific environmental conditions (e.g., flood, drought). The distribution of such species across different forest layers is summarized in Table 1.

Table 1. Species database: the involved species have been grouped into five vertical layers, according to their maximum height

Layer	definition (max height, H)	Species	# of species
1	max H <= 1	Lantern Chilli, Corazón de motelo, Hot pepper (Ojito de pescado), Pineapple, Uncucha, Manioc	6
2	1 < max H<= 4	Araza fruit, Camu-camu, Chacruna, Cocona fruit, Pigeon pea, Small sunflower, Lime, Papaya, Banana	9
3	4 < max H<= 15	Carambola, Orange, pacay (or ice-cream bean tree), Malay Apple, Pomelo, Inga (Shimbillo)	6

4	15 < max H<= 25	Aguaje, Coconut, brazilian Huasai, Mango, Breadfruit, Sapote	6
5	max H> 25	Brazilian nut, Copaiba, Dragon's blood (Sangre grado)	3

3.2. Problem formulation

The annual income ($y_s(t)$) per unit area from species s in each year t of the planning horizon depends on the production cycle of each species. It is defined through the time at which the first production occurs and the time of plant replacement. From the series of annual income, we can calculate the net present value (NPV_s, Mil Soles) of each species assuming a time horizon of *h* years and a given discount rate *d*:

$$NPV_s = \sum_{t=1}^{h} \left[y_s(t) / (1+d)^t \right] \tag{1}$$

For the present study, *h* is assumed equal to 15 years and *d* equal to 5%.
From the economic viewpoint, the overall objective to be maximized by an analog forest, where a certain number p_s of plants of species s are present, is defined as follow:

$$\max_{\{p_s\}} J = \left(\sum_{s=1}^{n} p_s \; a_s \; NPV_s\right) \tag{2}$$

where:
- p_s is the number of individuals for each species s (i.e., the decision variable);
- a_s is the area occupied by a single individual of species *s*
- *n* is the number of species considered
- NPV_s is the net present value of species *s* over horizon h

General constraints of the problem are:
- the use of land should be less or equal to the available land exposed to sunlight A_{tot}

$$\sum_{s=1}^{n} p_s \; a_s \le A_{tot} \tag{3}$$

- the decision variables are non-negative and integer.

$$p_s \ge 0, \text{integer} \quad \forall s \tag{4}$$

The last constraint (integrality), obviously plays a role only for large, sparse trees (layer 5) while becomes less and less relevant going down to the lower layers. The design of an analog forest should consider a fundamental structural characteristic: the presence of different vertical layers, from lower shrubs to higher trees (Sombroek and Higuchi, 2009). As previously described, we organized the considered species into five layers, *l*=1,…,5 (see Table 1). The deriving constraint is:

$$\underline{L} \le \sum_{s \in l} p_s \; a_s \le \overline{L} \qquad \forall\, l \tag{5}$$

where $\underline{L}$ and $\overline{L}$ are the lower and the upper bounds of the areal fraction of each layer, respectively, and $\sum_{s \in l} p_s \; a_s$ is the area dedicated to each layer (l), obtained by multiplying the number of individuals (ps) of each species s by the area occupied by each individual (as). In this study we set $\boldsymbol{L}$ equal to 0.1 and $\overline{L}$ equal to 1. The area dedicated to lower layers depends on the availability of both the surface exposed to sunlight and shaded one. The latter derives from the area occupied by the highest layers (i.e., 4 and 5). Moreover, we investigate how two further aspects may influence the performance of the designed agroecosystem, by defining two constraints. The first aspect we introduced concerns the intra-annual variability of income, which is determined by the seasonality of production of the various species. As previously said, these fluctuations strongly affect the livelihood of local communities, which relies on forest products. In order to avoid too strong variations, we set a constraint aimed at bounding monthly fluctuations of income over a year:

$$(my_{m+1} - my_m) \le f \quad \forall\, m, my_{13}=m_1 \tag{6}$$

Where:

- my_m is the monthly income of month m;
- f is a desired maximum variation of the monthly income. It can be set, for instance, as a fraction of the average monthly income (i.e. $y_s(t)/12$).

Secondly, as a preliminary assessment of ecological aspects, we evaluate the biodiversity of the obtained *analog* forest (S_{AF}) through the Simpson's diversity index (Simpson, 1949), calculated on the areal fractions :

$$S_{AF} = 1 - \sum_1^n \left(\frac{ps\ \ as}{A_{tot}}\right)^2 \quad (7)$$

where A_{tot} is again the whole available area. This index will be limited with a lower bound $\underline{\boldsymbol{S}}$ and different values of this bound will be set in the carried analysis:

$$S_{AF} \geq \underline{\boldsymbol{S}} \quad (8)$$

Once defined the problem, we first run the optimization in order to analyze the inter-annual variability of yearly income. Secondly, we assess how the introduction of different constraints (i.e., 6 and 8) influence the performance of the agro-ecosystem in terms of both of income and biodiversity. In this study, we assume an area of 50,000 m^2 as object of the planning problem.

4. RESULTS

4.1. Comparison of different planting strategies

The problem is a typical planning one, which assumes that the decision is taken once, at the beginning (year 0). The evolution of the agroecosystem and the derived income are determined by the occurrence of the first production and the replacement time of each involved species.

Assuming that (i) all the individuals are planted in the first year, (ii) that they all survive for their planned productive life, and then (iii) they are replaced all together according to the replacement time, we determined the optimal species mix and simulate the evolution of annual incomes over a 100-year horizon, constraining the presence of all the five vertical layers (eq. 5). In Figure 3, we report the obtained trajectory (grey solid line), whose periodicity is longer than a century, due to the different replacement times of the considered species.

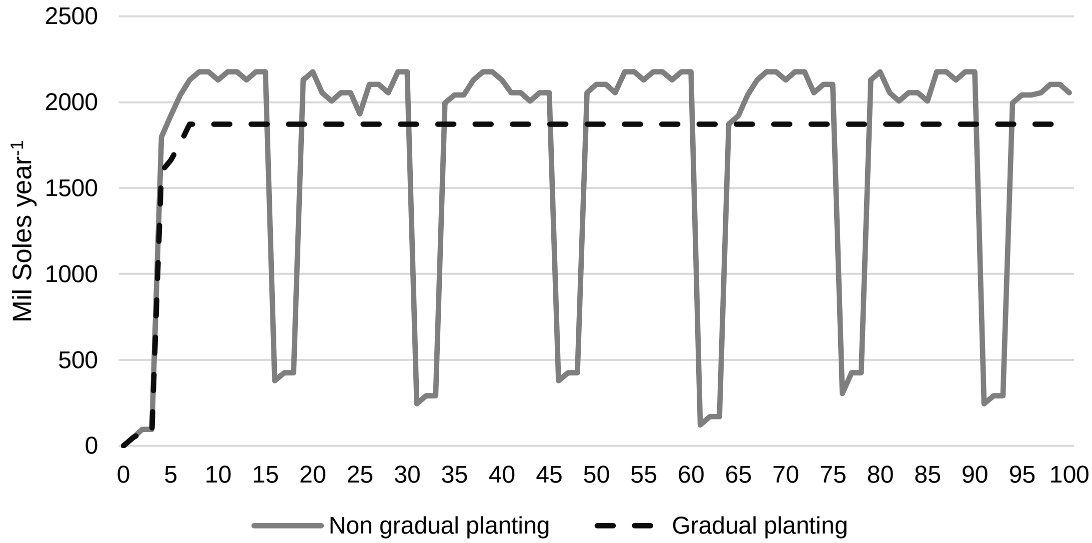

Figure 3. Comparison of two planting strategies: a gradual planting approach (dashed line) is able to eliminate the intra-annual variability resulted with the non-gradual approach.

Given the strong fluctuating behavior of incomes over the horizon (for three consecutive years the income may be only 12% of the average of the preceding 15 years), we introduce a smoothing mechanism: the plants belonging to the same species are gradually planted and replaced, in order to always have at least one individual of each selected species growing in the area. This also accounts for the fact that, during the planned productive life, some individuals may anyway need to be replaced for a number of reasons (e.g. pests, sickness, low productivity). The obtained trajectory (dashed line) is characterized by an initial transient period, but after 6 years it permanently remains at about 1870 Mil Soles/year (i.e. approximately the average value obtained by the full replacement policy). The removal (or at least the reduction) of inter-annual variability is a fundamental aspect for local communities in Madre de Dios. On the other hand, referring to the first 15 years, the NPV obtained with the second strategy is 13% lower than the former (i.e., 936 versus 1079 Mil Soles/year).

4.2. Economic value of constraints

Assuming the gradual replacement strategy previously described, we solved the above optimization problem (eq. 2) under different assumptions to investigate various economic and ecological aspects.
As a first step, we run the optimization to maximize the income, without setting any constraints on ecological or economic conditions. The obtained solution is the monoculture of *Camu Camu* (which belongs to the second vertical layer). Referring to the analyzed horizon (15 years), the derived annual NPV achieves the value of 1290.8 Mil soles, while the value of Simpson index is obviously null.

As a second step (case 2), we included the constraint regarding the presence of the five different vertical layers (eq. 5). In the obtained analog forest, the number of species increased from 1 to 5, i.e. an optimal one for each layer is selected, and the value of Simpson index improves up to 0.6. The second layer (i.e., between 2 and 10 meters, Table 1), the one including the most productive plant (*Camu Camu*), occupies 60% of the available area, while all the other layers are limited to the set minimum of 10%. On the other hand, the annual discounted income over the first 15 year decreased by 27% (i.e., 936.3 Mil Soles per year) when compared to the first result (case 1).

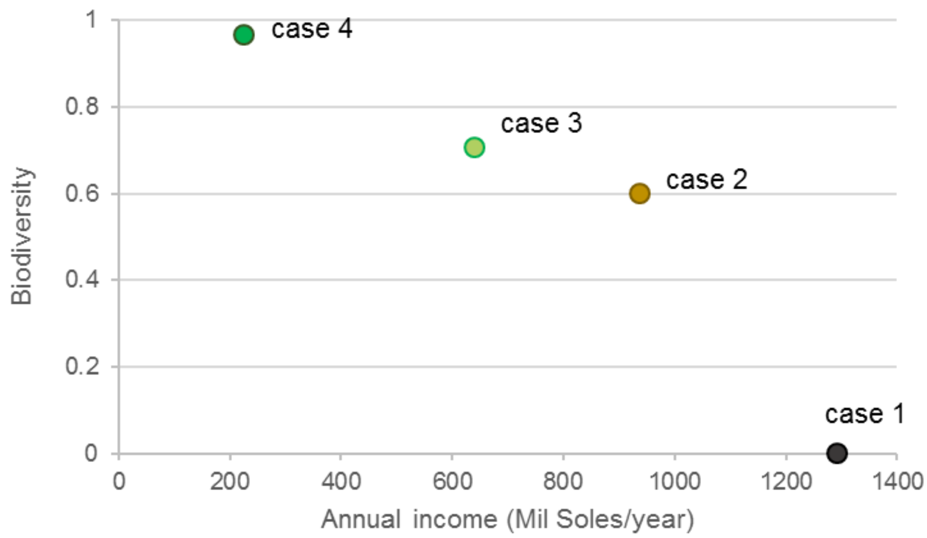

Figure 4. Economic and ecological performances of the analyzed planning problems.

As a further constraint, we introduced the limit to the intra-annual income variability (i.e., difference between monthly income, case 3). The annual NPV further decreases to 639.8 Mil soles (71% with respect to case 1), while the biodiversity index increases to 0.70 (the number of species becomes 6).

As a last step, we run the optimization by setting the high values (higher than 0.95) to the biodiversity bound $\underline{S}$ (eq. 8). The maximum value of $\underline{S}$ for which we found a feasible solution is S_{AF} = 0.97 (case 4). The obtained solution involves all the 30 species included in the database. Concerning the economic profitability, the resulting annual NPV is equal to 226 Mil soles/year, i.e., -82% if compared to case 1. The obtained results are summarized in Figure 4 on the plane Annual income – Simpson index, while Figure 5 shows how the available area is partitioned among the different layers.

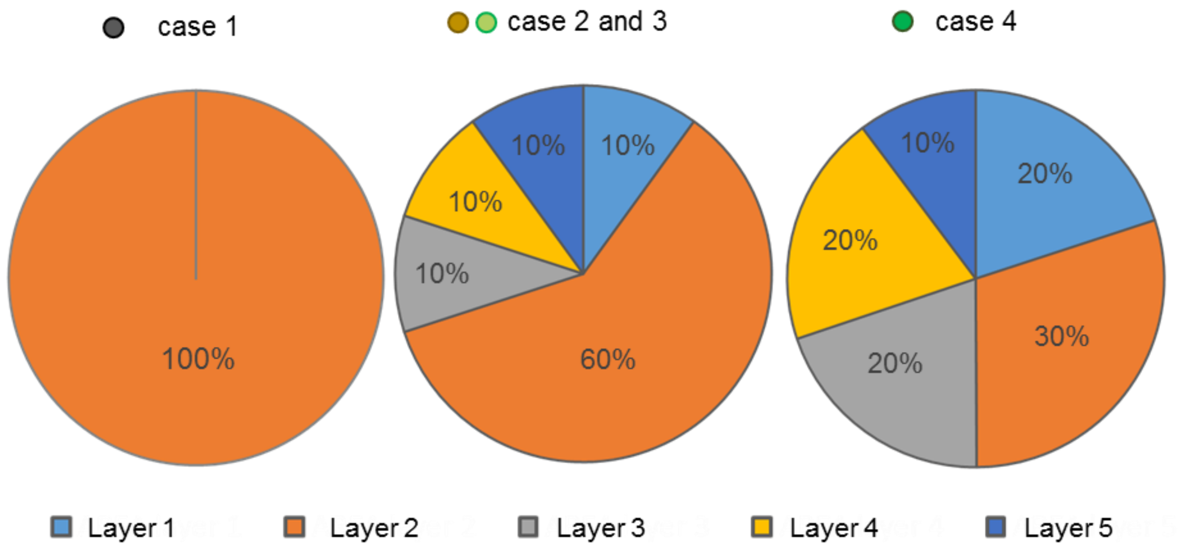

Figure 5. Partition of the designed agricultural area among the different vertical layers.

5. DISCUSSION AND CONCLUSION

In this study, we solved the planning problem of one of the most complex agroecosystems: the analog forestry. In particular, we focused on the Peruvian Amazon context, basing our analysis on the species database developed by ArBio association. We formulated a design problem which takes into account some relevant ecological aspects required by this agroecosystem, together with the economic ones.

As a first step, we analyzed the evolution of annual income and we compared two different planting strategies: a batch policy, in which all the individuals of the same species are planted and replaced together, and a gradual planting strategy, which guarantees the presence of each selected species in every year. The results show the positive contribution of the gradual strategy in terms of inter-annual income fluctuation when compared to the former one. This achievement is fundamental for the local communities, whose livelihood is based on forest production. On the other hand, when estimating the cumulative NPV over the first 15 years, the gradual plantation strategy causes a reduction of about 13%. In the second analysis, we quantified the changes in both economic and ecological performance of the designed agroecosystem obtained with different settings of the problem. In particular, we identify the two extreme solutions of the Pareto frontier: the maximum economic objective (i.e., NPV, calculated over the 15-years period) is obtained through a monoculture strategy (the selected species is Camu Camu, case 1), while the best biodiversity performance is achieved with a very diversified agro-ecosystem, involving all the 30 species available (case 4, i.e., obtained by setting high values of $\underline{S}$ in eq. 8). The economic objective decreases by 82% passing from the first solution (i.e., monoculture) to the second one. We then analyzed two intermediate solutions obtained by adding two fundamental constraints defined for this problem: the presence of different vertical layers, from shrubs to higher trees (case 2), and the minimization of intra-annual variability (case 3). The sequential introduction of these two constraints has positive contribution on the biodiversity index, but a negative one on the economic income (from -60% to -72% when compared to monoculture).

These quantitative outcomes can preliminarily support the determination of mechanisms for advising farmers, who decide to implement complex agroecosystems, like analog forestry, pursuing ecological goals. The average annual economic performance is affected by the introduction of ecological constraints and biodiversity, but on the other hand, these choices allow to preserve important ecosystem functions within the agro-ecosystem, which may lead to the reduction of cultivation costs, which have not been considered in this study. Of course, this work represents a preliminary attempt of addressing the design of such a complex agroecosystem in the Peruvian context. Future developments will need to improve plant dynamics, introduce spatial analysis of plantation (e.g., distances between trees and shadow interference), as well as other ecological aspects like nutrient balance and carbon storage. Moreover, a more flexible management strategy may be adopted in order to optimize the transient period/s, where higher species do not have achieved their maximum dimension yet, and a wider sunny area is available for lower annual crops.

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