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Article

Repopulating and Rewilding a Historical Agricultural Landscape: 2030–2100 Transition

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Abstract: Spain is at the forefront of organic agriculture in Europe and entering carbon farming but is facing rural depopulation, draughts, soil erosion and pervasive glyphosate pollution in water. These are factors affecting the rural ecosystem, which is simulated here as a 4-species Lotka-Volterra model from 2030 through 2100. The role of interstitial permaculture (IP) in solving for land fragmentation and loss of local agricultural knowledge and practices, is explored. Landscape ecology, and especially the role of hedgerows in bocage and *dehesa* landscapes give credence to IP as a form of agroforestry. The Lotka-Volterra simulation captures the high interconnectedness of species in the local agroecosystem. The simulation also provides insight into the limits of a viable transition to sustainable agriculture: reforestation is fostered by the inflow of permaculturists, but wolves cannot by themselves stem the tide of boar growth. Rather, human intervention throughout Europe seems to be required. Eventually, the model manages to bring boar, wolf and human populations to a certain balance, oscillating near the carrying capacity of the system, but tree populations keep well below carrying capacity, suggesting more reforestation efforts. The ecobenefits resulting from the ecosystem's evolution fostered by permaculture were found to be in terms of soil protection hence soil organic carbon sequestration. A striking suggestion of the model regarding herbivory is that boar meat should be consumed by humans, a practice in the area during the Holocene, and supported by new research in Europe.

Keywords: permaculture; Lotka-Volterra; depopulation; rewilding; carrying capacity; soil protection

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1. Introduction

Sustainable agriculture has a pivotal role to play in solving global change issues; not only must it reduce its water consumption and pollution, its carbon footprint, and its role in critical global soil erosion (Evans et al., 2020). It must also contribute to natural land cover recovery, rewilding, and the provision of safe food and employment.

Locally, climate change, and especially increased frequency and severity of droughts is hitting the agricultural area of Salas de los Infantes, in the historical heartland of Spain, a country viewed as a climate change laboratory for Europe (Agrospecials, 2023). Salas is surrounded by five Natura 2000 European Union protected areas (Figure 1). The area also belongs to the ageing and "deserted Spain": it has lost population for 50 years to the large industrial cities of Bilbao, Madrid and Barcelona.

By 1980, the remaining agriculturalists had embraced Green Revolution agrochemicals and machinery, and more recently, fast-growth monoculture woodland. And so, in this hilly region, erosion is high and glyphosate water pollution is, per official accounts, omnipresent (Subdirección General de Protección de las Aguas y Gestión de Riesgos, 2023).

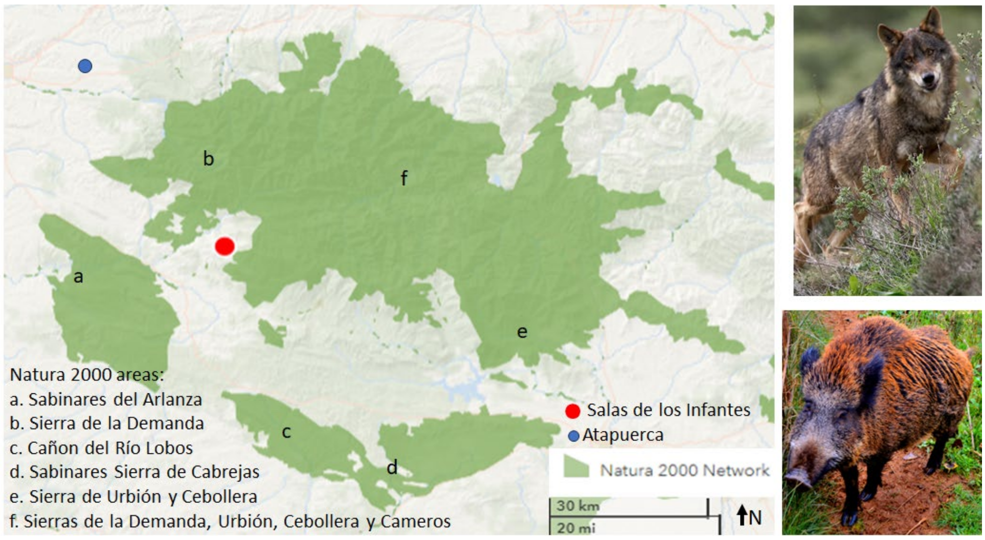

Figure 1. Feasibility of rewilding. Salas is located within a set of nature reserves of European importance. Human presence dates back to 1.3 million years BP in Atapuerca. Sierra de la Demanda is also among the top ten Spanish areas for observing wolf (*Canis lupus* signatus) and its potential role in controlling boar (*Sus scrofa*) population.
Sources: Anthiro 57, 2016; European Environment Agency, 2021; Tudela de Duero, 2016.

A bifurcation needs to take place in areas like Salas. Business-as-usual would turn the area into an extractive economy area. Already, depopulation is seen, in the long game of mining and the energy sector, as an opportunity: decommissioned nuclear power plants in the province are never really shelved for good (Caubilla, 2022) and uranium is present in Salas (Sánchez & López, 2021) so prospection could be revived. Windpower turbines already straddle the region. Contrariwise, sustainable agriculture can revert depopulation and produce healthy foodstuff in a manner appropriate to local climate, protect the local pharmacopeia heritage knowledge, protect soil and water resources, and combine heritage landscapes and practices and current landscape ecology to protect crops from frost, wind desiccation, excess solar irradiance and temperature, herbivory, and excess evapotranspiration.

1.1. Theoretical Underpinnings

Permaculture and ecology ascribe a prominent role to systems theory, as expounded by Bertalanffy in 1934. This theory guides the integration of elements, such as plants, animals, and humans, to enhance the resilience of the whole system. The theory also emphasizes the integration and adaptation of subsystems: landscape ecology, functional diversity (primary producers, herbivores, predators, human stewards), and resilience to disturbances.

In terms of scientific method, the trophic network and IP are modules that are described and simulated. In the simulation, modularity means there is no limit to the number of interconnected subsystems (species) nor a limit to the number of functions and parameters that relate any two species. An account of the system limits imposed by interconnectedness can be given by sensitivity analysis. The modular object-oriented method befits the system theoretic approach and a problem-solving definition of science, as proposed by Herbert Simon in the 1980s.

1.2. Interstitial Permaculture, Rewilding and Repopulation

Permaculture is a set of sustainable production techniques for food security, ecosystem restoration, and social revitalization that integrates plants, animals, and humans into healthy coupled human and natural systems (CHANS). Permaculture creates productive synergies conducive to developing community-driven economies (Ferguson & Lovell, 2019) and enhances the ability of CHANS to self-sustain by improving soil, supporting wildlife and conserving water (Hirschfeld & Van Acker, 2021).

In turn, IP is permaculture in underutilized, neglected or unused rural spaces: it has a potential for non-confrontational land use change. Initially transforming urban unused spaces into productive ecosystems, efforts are being made into applying new technologies to enhance sustainability (Concepcion et al., 2021). By fostering local food production, IP helps communities become more resilient by reducing their vulnerability to external food supply shocks. IP also promotes carbon farming, stormwater management, and soil regeneration, which are vital for improving environmental health.

Permaculture and rewilding are complementary approaches to ecological restoration and sustainability: while IP mimics natural ecosystems, rewilding focuses on allowing nature to restore itself by minimizing human intervention. Both prioritize biodiversity, trophic networks in balance, and long-term sustainability. IP however tries to minimize the cultivated area, maximize yearlong nutritional output, use belowground automated fertigation, use natural succession to develop hedgerow protection against desiccating and eroding winds, frost, excess solar irradiation and evapotranspiration, runoff erosion, use water harvesting, renewables, vegetation waste and humanure biorefinery. IP also benefits from reforestation in the form of green corridors and waterholes for pollinators and seed dispersers. By striving for nutritional self-sufficiency and the use of a local pharmacopeia, IP fosters the recovery of heritage agricultural knowledge.

To understand future land use, and IP as a non-confrontational driver of land use change, one must look back at how land use change and tenure upheavals are historically concomitant: While medieval land use change was driven by wheat and wine production, the *dehesa* silvopasture tried to prevent conversion to extensive cereal culture; the *dehesa* also benefitted the *Mesta* guild and transhumant merino sheep. Commons date back to before the 16th century Castille *Comuneros* rebellion. The challenge to commons by competition for land by nobility and clergy is just as old. Thereafter, commons and clergy lands were challenged by the liberal push for private property, extensive agriculture and husbandry under 19th century monarchic and republican rule. Under the 20th century republic, cooperative and union movements became a force (Beltrán Tapia, 2012) repressed by Francoist rebellion against the republic. The incarceration, execution, and exile of cooperativists and unionized rural workers, and the eviction of their families, jumpstarted a rural exodus to urban industries. Under Franco, afforestation with tree diversity loss took place under the aegis of a state corporation. In a way, Salas has historically been interstitial, being less intensively and extensively cultivated than the area surrounding Burgos, the provincial capital. In future, agricultural and ecological policies are likely to retain a degree of past tenure and land use ideological conflicts. Arguably, the forces behind future sustainability embrace the use of commons.

In turn, land use has altered interactions between species and will continue to do so in future. Evidence of a Medieval Climatic Optimum has been inferred from recorded wheat production increases, ensuing population rise, and deforestation. This led to forest protection under the late 15th century and early 16th century rulers. This protection contrasted with the long-lasting clergy opinion in Western countries against wolf and a host of other animals. Hunting and forest disturbances have taken their toll too. The Spanish wolf meta-population has declined, local wolf populations are becoming disconnected, inbreeding and breeding with dogs seem on the rise, despite some evidence of genetic flows from across the Pyrenees. As to the ongoing wild boar surge, it is a byproduct of wolf decline (about a third of wolf diet includes boar, particularly piglets) and boar feeding on irrigated maize, wheat and potato. Boars also heavily rely on energy-rich acorns, especially during fall and winter. This, and trampling, affects acorn survival, germination and the number of seedlings. Wolf depredation on livestock occurs in remote locales. Recently, wolf hunting was banned in Spain to comply with European Union rules, but some EU parliament members and the incumbent EU Commission President might try to reverse said rules. In 2024, the EU Nature Restoration law was enacted, with specific member States obligations regarding reforestation. Again, ideological viewpoints are likely to clash in future.

Significance of This Study

Owing to the rewilding trend, any rural repopulation effort should account for its net impact on the other species (and here, its impact on wolf reintroduction, reforestation and boar control). This account hinged firstly on a simulation of trophic dynamics. And secondly, on a demonstration that humans can be stewards of a trophic network; this amounted to showing IP as a solution to one problem: how humans can help nature so nature can help them.

1.3. Goals

This paper deals with future agricultural landscapes and the ecological matrix in which they occur. Formalization and implementation of a model for a rural ecosystem was necessary as multiple connections (in a simplified trophic network, Figure 3) preclude intuitive predictions of action (or policy) outcomes. The policies of repopulation and rewilding were at stake here. Therefore, the goals were to represent trophic network dynamics as a mathematical model of populations that responded to a matrix of relationships between species. The model needed to identify the limits within which the species operate and transition from unsustainable to sustainable states (from 2030 through 2100), supported by IP.

2. Method

A dynamic model of the 2030–2100 transition to a sustainable agroecosystem was grounded on feasibility elements, so firstly, a locally relevant form of sustainable agriculture was characterized (IP) to solve for today's land ownership fragmentation. Secondly, historically important agricultural practices (*hacenderas*, village shepherd and shepherd guilds) and landscape elements (e.g., commons: *eras*, *ejido*, *dehesa*, and also bocage and hedgerows) were identified as local accumulated knowledge and accepted practices. Thirdly, the nature-rural population matrix was formalized (as a 4-species Lotka-Volterra logistic/sinusoidal growth). A sensitivity analysis helped understand the interconnections in the ecosystem (Supplementary Materials). The Python code for this model is available at https://github.com/EmmanuelCastillo87/Sus-Scrofa/tree/main. Fourthly, the results showed some of the limits of rewilding and human repopulation, as well as practices adjuvant in seeking ecological balance. And fifthly, the ecobenefits of IP were identified.

3. Results

3.1. Interstitial Permaculture

Land fragmentation was identified as a factor in land disuse. IP would take advantage of marginal lands that have not been subjected to land concentration (Figure 2), and still harbour highly valuable bocage landscapes (Figure 3). The value of bocage stems from being a tight network of hedgerows able to regulate temperature and solar irradiance and thus reduce evapotranspiration, frost, and wind desiccation. Hedgerows can also halt herbivory and the progress of pathogens through the landscape. As to permaculture, i.e., permanently producing agriculture with a high degree of produce diversity and high nutritional quality and food safety, it seems a requirement to attract younger generations with evolving nutritional preferences (discussed below).

Figure 2. Cadastral map, Salas area. Land ownership fragmentation (small size, dispersion and shared ownership) suited to IP in bocage landscapes. Dispersion among vicinities suggested different ecotopes hence exposures to weather, herbivory and pathogens.

Table 1. Typical fragmentation of one property into plots located in different vicinities. The names of the vicinities depict ecological features.

Vicinity	**Area (m^2)**
Cerro (hill)	549
Valle (combe)	717
Mese (harvest or grain or masiega - herbaceous plants)	1,135
Ladera (hillside)	59
Ladera (hillside, shaded green plot in Figure 2)	245
Moje (small boundary stone)	1,357
Corzas (female roe deer, Capreolus capreolus, in a sheltered valley)	1,094

Remnant bocage plots persist, and even tractor-tilled plots preserved scattered trees in 2023, suggestive of *dehesa* landscapes that mixed trees and other uses (Figure 3). *Dehesa* (from Latin *defensa*, defense) mixed other uses with trees to avoid clear cutting. Bocage is a succession of faster, then slower growth trees. Among the latter *Pinus sylvestris* and *Quercus pirenaica* are the most abundant in the study area. In IP, fast growth berry shrubs should be added. Beyond the bocage, native wild herbaceous species (such as *Carex camposii*) should be protected for their value. Permaculture is best taken care of by the whole household so dwellings should be incorporated into the bocage landscape.

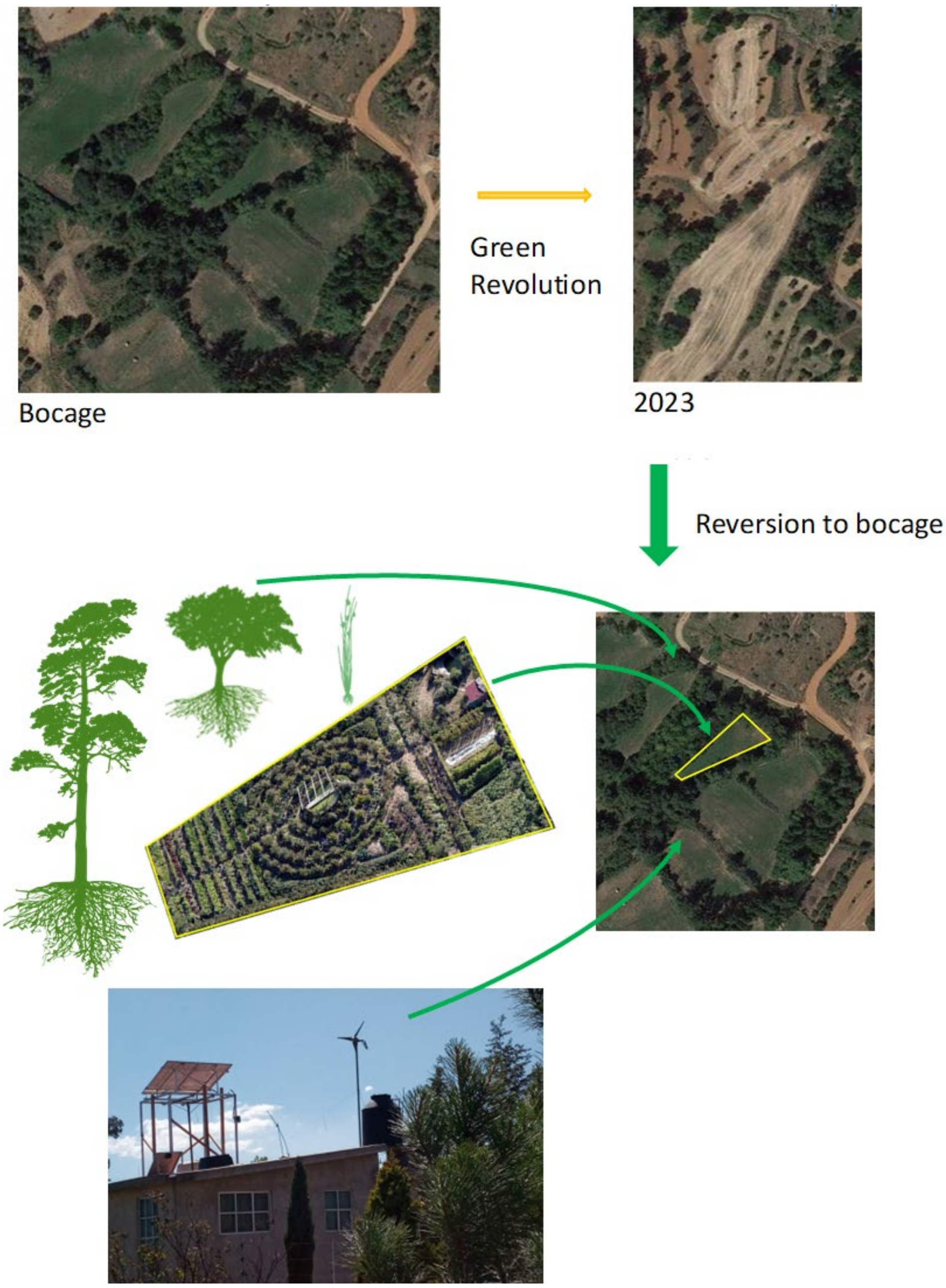

Figure 3. Historically important agricultural practices and landscape elements.
Sources: Alôsnys, 2016; Instituto Geográfico Nacional and Google ©2023. Solar roof atop a live-in lab: © de las Heras and Islas-Espinoza.

3.2. Trophic Model of the Rural Ecosystem

A key result of trying to bring humans and nature closer together, as they once were before the 1980s in the study area, was the formalization of the repopulation-rewilding link. The formal expression took the shape of a logistic curve, used for over a century in statistics, demography, ecology, microbiology and now, artificial intelligence. The curve depicts growth up to the limits of a system (Figure 4). After reaching the limit of the system, all present species, if behaving like natural populations, should oscillate sinusoidally around the limit for each species imposed by the whole system (Figure 5). The number of *Quercus* trees that bear acorns was included in the trophic model. Wolf had a role in controlling boar, and humans had an impact on tree, boar and wolf populations. An interaction matrix was an additive element to the logistic-sinusoidal Lotka-Volterra model. Of note is the amplitude parameter A which could be interpreted as (non-random) variation rather than a single-valued limit to the growth of a population.

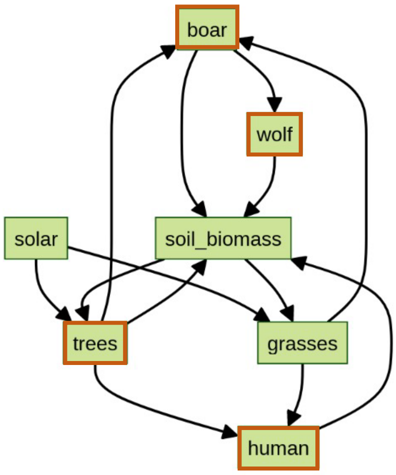

Figure 4. Trophic network. The boxes outlined in red were explicitly modelled. Acorn was the part of the trees that was factored in.

The Lotka-Volterra model was:

$$P_{i,t+1} = P_{i,t}(1+r_i)\left(1-\frac{P_{i,t}}{K_i(1+A\sin(\frac{\pi}{4}t))}\right)+\sum\frac{\alpha_{ij}P_{j,t}P_{i,t}}{K_i} \quad (1)$$

r_i is the population intrinsic growth rate.
$P_{i,t}$ is the current population.
K_i is the carrying capacity.
A is the amplitude (height) of the sinusoidal variation near K_i (the base model used the values in Tables 2 and 3).

Table 2. Lotka-Volterra base model, values of parameters.

	r	**P_0**	**K**	**A**
Acorn	0.015	31,300	122,000	0.1
Boar	0.5	300	6,000	0.1
Wolf	0.4	4	12	0.15
Human	0.106	1,900	28,500	0.05

Table 3. Lotka-Volterra base model, interaction matrix (α_{ij}). Column species j controlled row species i (each j individual had an ij controlling effect which was multiplied by the i and j populations).

	Acorn	**Boar**	**Wolf**	**Human**
Acorn	0	−0.1	0	−0.1
Boar	0	0	−1	−0.9
Wolf	0	0	0	0.00039
Human	0	0	0	0

The limits of the trophic network were given by the interplay of the parameters r, P_0, K and A. The model showed that gradual reforestation could accompany an increase in human population (Figure 5). Also, reforestation needed to be higher than just bocage. But boar could not be controlled solely by wolf, as wolf population was limited by wolf large range for enough prey to exist; and wolf could only grow to a level that avoided conflicts with husbandry. Even large wolf growth rates could not match the dynamics of boar which suggested that the natural landscape and agricultural plots were feeding boar, and that human consumption of boar should be factored in.

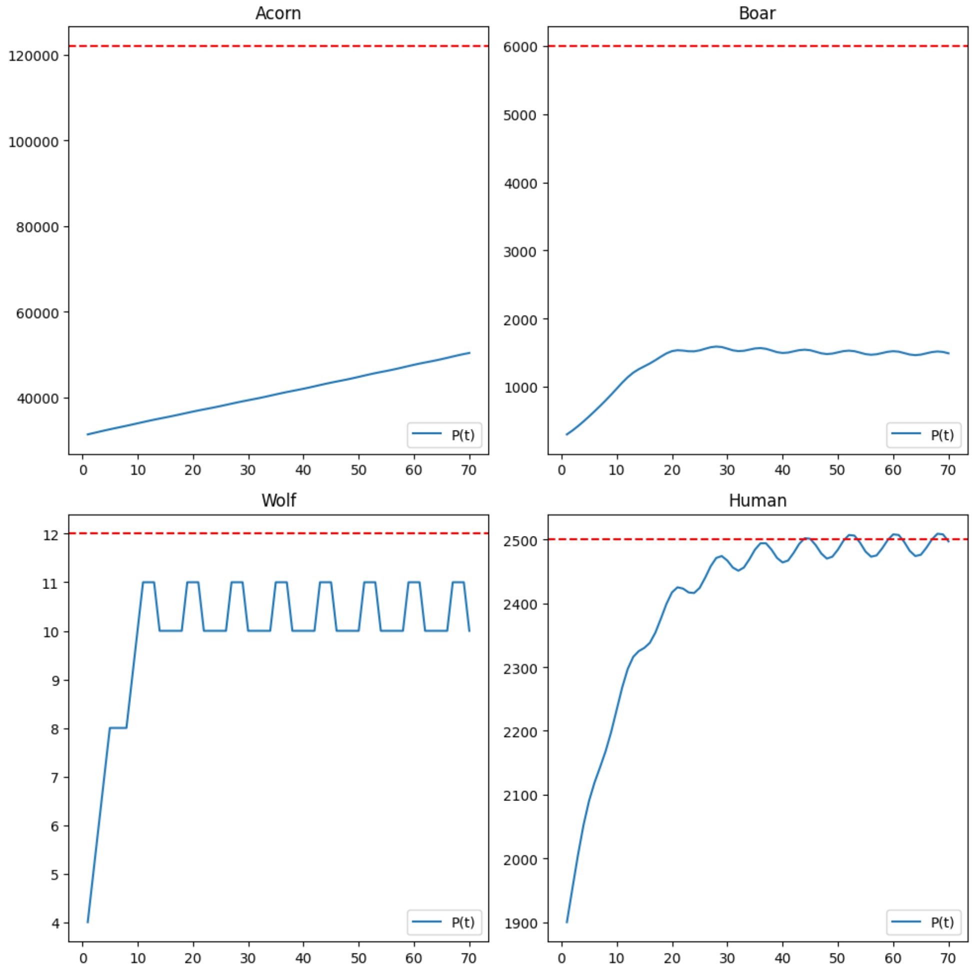

Figure 5. The human repopulation – rewilding base model. "Acorn" stands for trees producing acorns, which are among the most energy-rich boar feeds. Boar in turn was central in this trophic network, as it fed on acorn and fed wolf. Humans participated in reforestation and wood consumption, wolf reintroduction and boar consumption.

The Lotka-Volterra model showed an increase in acorn-bearing trees from 31 thousand to 50 thousand. At a reforestation density of 1000 trees per square kilometer, this was a 19 km^2 reforestation. Reforestation, in addition to its direct carbon sequestration, had an indirect contribution via its role in erosion control. The reduction of soil erosion ensuing reforestation was 0.12 t/ha/yr soil C sequestration (FAO, 2024) despite 2.2 t/ha/yr soil loss (Comunidad Autónoma de Castilla y León, 2012).

But the model also highlighted the difficulty in reaching the tree carrying capacity, due to the pressure exerted by boar and humans. Boar in this model was successfully controlled by human pressure. Wolf pressure on boar however was very limited due to the small predator population. Boar ended the transition at less than a third of the population predicted by its current trend.

Trophic Model Sensitivity Analysis (21st Century Scenarios)

Qualitatively, the simulations produced variants of two scenarios: Sustainable repopulation and rewilding, and Extractive rural world. The upshot is that human growth up to carrying capacity and pressure on boar would allow for reforestation, with wolf a necessary predator whose functional role in the ecosystem is thwarted by humans. Under Sustainable repopulation and rewilding (the reference model, Figure 5), boars were controlled well below their possible maximum population, humans grew from 2030 through 2050, but the timber industry limited reforestation. In the Extractive rural world, continued human depopulation prompted a continued boar surge.

3.3. Interstitial Permaculture and Rewilding Benefits

When the permaculture and ecological strands of this study are brought together, it appears that repopulation and rewilding can be mutually beneficial. Benefits for every invested Euro are 4-38 Euro (Directorate-General for Environment, 2024). The values in the Lotka-Volterra model parameters determined the ecobenefits of permaculturists (Table 4). Human repopulation (from 1,900 to 2,500 dwellers in 70 years), if driven by in-migration or immigration of interstitial permaculturists contributed only a small additional ecological footprint, compensated for by improved practices and ecobenefits. Job generation (based on 2 permaculturists per permaculture and 2 dependents, for a total increase of 600 persons) was 300 jobs. This occurred at carrying capacity level and, in an ageing rural hinterland, was a valuable increase.

Table 4. Interstitial permaculture and rewilding benefits.

Rural change	Solutions to agricultural issues	Solutions to global change issues
Human repopulation	Stable job generation by permaculture. Recovery of local knowledge, practices and commons.	Stewardship of abandoned land. Local knowledge added to global scientific assets.
Bocage reforestation	Reduction of soil erosion. Regulation of evapotranspiration in the plots.	Mitigation of solar radiation forcing. Hedgerows as obstacles to herbivory and pathogens reduce the need for agrochemicals.
Interstitial permaculture	Increased nutritional density and innocuity of foodstuff. Recovery and protection of wild and cultivable medicinal and edible plants.	Carbon farming. Local production reduces the carbon footprint of foodstuff transportation.
Wolf reintroduction	Control of wild boar and zoonoses. Control of boar herbivory impact on cereal production. Ecotourism.	Change in the framing of predator issues in the press and political discourses.

4. Discussion

This study departed from studies on the limits of Earth's life support system and instead tried to pinpoint the limits of a viable space at a scale where models are actionable. Rural issues are multifarious and highly interconnected. This makes agricultural and rural policy outcomes difficult to predict. Calls for agriculture planning seem to be on the rise, but mostly rely on data repositories without mentioning that actionable models of dynamics and high interconnectedness are lacking.

Globally and locally, sustainable agriculture could help solve its own environmental footprint, while agroforestry can help in carbon sequestration via protection of soils (against erosion brought about Green Revolution mechanical and chemical technologies). This approach to agriculture is termed Carbon Farming and is embedded in the 2023 official Spanish policy approved by the European Union for its new Common Agricultural Policy (Directorate-General for Agriculture and Rural Development, 2023; McDonald et al., 2021). Salas has the second lowest soil loss in the Burgos province (Comunidad Autónoma de Castilla y León, 2012) and IP, agroforestry and reforestation could accrue revenue in the Carbon Farming certification schemes now developing. Caution is warranted however, regarding carbon schemes which could derive into monoculture afforestation with fast-growth species. This would derail the transition to sustainable agriculture. Recent research shows that permaculture enhances soil carbon content and biodiversity (Reiff et al., 2024).

Locally, human repopulation was found to rely on an IP embedded in the local trophic network. In this network, the largest trees and mammals were accounted for (save for cattle). The most striking suggestion of the simplified trophic network was that boar consumption by humans was likely needed to compensate for agricultural losses attributable to boar and because boar meat is more sustainably produced than pig meat; both meats are indistinguishable genetically and in taste (Machácková et al., 2021; Sales & Kotrba, 2013; Strazdiņa et al., 2013). The history of boar and pig consumption by humans in Atapuerca, a few kilometers from Salas, spans the Holocene (Galindo-Pellicena et al., 2024). Another justification for boar control are zoonoses; they have prompted a European reaction, and in the Castilla y León community and Salas, the enactment of an order to augment hunting pressure on boar (Boletín Oficial de Castilla y León, 2024).

The ongoing nutrition transition with lessened environmental impacts in Spain includes the noticeable increase in consumption of vegetables and diminution of meat consumption, especially among younger generations (Lantern, 2021). Concomitantly, Spain is the European leader in organic agriculture (Agrospecials, 2023).

Policies and Simulation of Rural Future

It is a sobering fact that policies are fraught with side-effects and non-coordination (especially between agricultural and ecological policies), which call for simulations prior to discussion and implementation. Based on the insights gained from documenting the feasibility of IP and the simulated future trophic network, the following recommendations emerged:

1. Sustainable land use management policies are crucial in degraded regions.
2. Forest and land policies aimed at increasing connectivity and biodiversity through reforestation programs align with IP.
3. Wild boar population control: Effective management strategies include reducing food availability, selective culling of younger wild boar, and controlling access to feeding sites. These methods have been tested in peri-urban areas to manage populations and can be adapted to rural areas. Promoting humane culling would largely improve the quality and market value of wild boar meat. Culling piglets is more efficient than culling adults as fewer boar-years are spent impacting environment and crops.
4. Wolf reintroduction: Integrating a keystone predator into land use management helps naturally control wild boar populations. Policies should incentivize farmers to maintain free-ranging livestock systems that coexist with wolves, as these systems contribute to ecological balance while minimizing human-wolf conflicts.
5. Permaculture and human repopulation: This could be supported by regional policies focused on sustainable land and water management, fertigation plans and automation that aim to balance environmental and economic goals. Policies incentivizing sustainable agricultural practices, like rotational grazing and reforestation, could create jobs and attract people to rural areas while improving the ecological health of the region.
6. Subsidize sustainable agriculture preferentially. Sustainable agriculture requires land not to be chronically overused, not overpopulating terroirs, integration in the larger ecosystem, no debt-financed Green Revolution technologies and non-exploitative use of labor. Subsidies should favor technologies such as: no tillage, rotation, waste recycling, use of renewables, biological control, automated belowground fertigation, hedgerows, participation in carbon farming.

Specific policies with a potential for supporting IP include:

(1) Zoning regulations that encourage the repurposing of vacant land for permaculture projects. Flexible zoning can allow for community agriculture.

(2) Subsidies, such as grants or tax breaks, for individuals, cooperatives and communities engaging in permaculture practices on interstitial land for ecological restoration.

(3) Community Engagement and Support in permaculture through educational and training programs can enhance social cohesion, knowledge preservation and healthy ecosystems. Ongoing intergenerational attitude shifts are best fostered via educational programs.

(4) Research policies, agricultural extension and citizen science should evolve into collaborative inquiry with permaculturalists and live-in laboratories.

(5) Public awareness campaigns and partnerships between local governments and grassroots organizations are critical to supporting IP.

Supplementary Materials: The following supporting information can be downloaded at: https://zenodo.org/doi/10.5281/zenodo.13740794, Sensitivity analysis.

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