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Building a Restorative Agricultural Economy: Insights from a Case Study in Santa Catarina, Brazil

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Abstract: Agriculture is the most important economic sector and simultaneously the greatest threat to the ecosystem functions on which all complex life depends. It is therefore a logical starting point for developing a restorative economy. We must develop and disseminate agroecosystems capable of providing food security for all, while simultaneously restoring vital ecosystem processes degraded by conventional agriculture. We review 25 years of transdisciplinary work towards this goal on an agroecology project in Santa Rosa de Lima, Santa Catarina, Brazil and distill some key lessons for like-minded efforts. We apply the methods of Participatory Action Research and Post Normal Science to integrate the knowledge, insights and goals of farmers, diverse scientists, agricultural extensionists, and policymakers to design high-biodiversity silvopastoral systems and multi-function riparian forests capable of improving farmer livelihoods, and propose policies to support their adoption by aligning the interests of farmers and society. We explain the science underlying our project and document resulting improvements in farmer livelihoods and ecosystem services. We then examine the socioeconomic obstacles to disseminating our innovations and policies that might overcome them and describe our pragmatic approaches to working with policymakers. We conclude that integrating natural sciences, socio-economic analysis and politics are all necessary yet insufficient to promote the large-scale adoption of restorative agriculture. We contend that building a restorative economy will also require a fundamental extension of humanity's moral values to the rest of nature, and use evolutionary science to support our views. Rather than offering a recipe for successful projects, our take-home message is that developing a restorative agricultural economy in an ever-evolving system is a continuous participatory process with no endpoint.

Keywords: agroecology; ecological economics; restorative economy; participatory action research; farmer livelihoods; policy; sustainability ethics



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1. Introduction

Scientists have defined nine planetary boundaries that humanity cannot exceed without risking catastrophic impacts to global ecosystems. Agriculture has already pushed us past safe limits for at least five of these boundaries (biosphere integrity, novel entities, biogeochemical flows, climate change, land use change) [1–3], making it among the greatest threats to global ecosystems [4,5] and the life-sustaining ecosystem services they generate [6], including many that support agriculture itself [7,8]. These ecological costs of conventional food systems pose an existential threat to humanity. At the same time, nearly one billion people are currently undernourished, the global population continues to increase [9,10], and climate change threatens dramatic disruptions to global food supply [11,12]. Inadequate food production and distribution poses an existential threat to the world's poor. We recognize that scholars have been warning of imminent mass starvation since the times of Malthus [13–15], and that to date technological advances have

staved off this outcome. However, the technologies that have allowed food production to outpace population growth for so long are the same ones driving us beyond planetary boundaries [16–18]. Both food and ecosystem services are essential to human survival.

Developing and disseminating a restorative agricultural economy is no simple task. We present here a review of our work with small family farmers in the municipality of Santa Rosa de Lima (hereafter Santa Rosa), Santa Catarina, Brazil, located in southern Brazil's Atlantic Forest, to illustrate some of the major challenges to building a restorative agricultural economy, and discuss our efforts to overcome. This project was initiated over 25 years by a collective led by co-author Schmitt-Filho, with co-author Farley as an intermittent team member since his sabbatical year in UFSC in 2009 [19–21]. Our work integrates the approaches of agroecology and ecological economics.

Brazil's Atlantic Forest manifests the global conflict between agriculture and ecosystems in a microcosm, making our case study site particularly appropriate. The biome is a biodiversity hotspot [22]. It is also home to 62% of Brazil's hydropower capacity, 75% of its drinking water and 72% of its human population [23], who depend on the ecosystem services it provides. Only 13–28% of the original forest remains, depending on how small a fragment is considered forest [22,24], yet ecologists estimate that if forest cover remains below 30%, there will be a massive reduction in biodiversity and the ecosystem services it generates, with unpredictable yet likely catastrophic consequences [25]. Time lags between forest loss and extinctions may provide a narrow window of opportunity to restore adequate forest cover to avoid this threshold [26,27]. However, with current agricultural practices, converting farmland to forests threatens family farmer livelihoods, and potentially the ~70% of Brazil's domestic food they supply, potentially plunging them into poverty [28]. The choice between ecosystem collapse and poverty is unacceptable.

Our work is dedicated to developing and disseminating agroecosystems capable of restoring and rehabilitating the Atlantic Forest ecosystem while increasing food production, improving farmer livelihoods, and complying with Brazilian laws mandating forest protection and restoration. Santa Rosa is considered the agroecology capital of Santa Catarina and the Federal University of Santa Catarina (UFSC) has been engaged in participatory action research (PAR) here with multiple stakeholders since the late 1990s [19–21]. Our team, the Silvopastoral System and Ecological Restoration Lab (UFSC/LASSRE, previously the Voisin Grazing Group), is collaborating with farmers and other stakeholders to develop and disseminate agroecological alternatives to chemical intensive annual agriculture.

Our goal with this review article is not to focus on specific project findings in detail, which we have done in many of the articles we cite (e.g., [28,29]), but rather to extract valuable lessons from our experience that can help inform other efforts to build restorative agricultural economies. Creating a restorative agricultural economy is often viewed as a technical problem best solved by scientists [30], or as an economic policy problem best solved by providing appropriate incentives [31]. The overarching lesson from our research is that transforming complex socio-ecological systems requires a transdisciplinary approach, which means not only drawing on theories, methods, tools, and insight from multiple disciplines, but also transcending disciplinary frameworks all together to integrate the knowledge, values and insights from the myriad stakeholders involved. Today's problems are often caused by past "solutions" that neglected this principle [32].

Sections 2 and 3 of this review provide a brief overview of our general methods and a description and agricultural history of Santa Rosa. Section 4 addresses the technical challenge of developing agricultural practices that can restore ecosystem functions without threatening food production or farmer livelihoods, which requires the integration of agronomy, ecology, and economics, along with the participation of local farmers and other stakeholders. Section 5 focuses on social and economic challenges of disseminating restorative agriculture across farming groups at a meaningful scale when innovation is risky, and farmers have few resources to invest and cannot afford to risk a loss of revenue. Section 6 addresses the political challenge of designing and implementing policies that can bring individual land use decisions into better alignment with social interests, which

requires collaboration with policymakers and farmers to develop policies that promote farmer adoption and mitigate risk. We have made significant progress on all these aspects, but ultimately recognize they are inadequate. Section 7 conjectures that lasting solutions will require fundamental ethical changes in the way individuals relate to land, society and nature. We apply evolutionary theory to explain why such changes may be necessary and suggest how we might achieve them. Section 8 provides a summary and conclusions, emphasizing the need for a participatory, transdisciplinary approach to building restorative economies.

2. A Brief Overview of General Methods

Our research project integrates the closely related fields of ecological restoration, agroecology and ecological economics. These fields are highly transdisciplinary and dedicated to solving real life problems. Conventional scientists are taught a set of disciplinary methods and tools they apply to any research topic. In transdisciplinary, action-oriented research, the problem determines what tools and methods are required to solve it. Transdisciplinary work not only integrates the natural and social sciences, but also transcends academic disciplines all together to integrate local knowledge and experience [33,34].

Our project utilizes the methods of participatory action research (PAR) and Post-Normal Science (PNS). The former is generally associated with agroecology and state-of-the-art ecological restoration initiatives, and the latter with ecological economics, but they share much in common besides transdisciplinarity.

In PAR, research topics are determined in close collaboration with farmers and other stakeholders, typically to advance stakeholder goals. In an iterative process, research participants periodically reflect on their progress, goals, and methods, and adjust their efforts accordingly [35]. The process requires trust, which must be built over time. Our project applies the following steps: (1) listen to the needs of organized groups of farmers; (2) present our suggested agroecological solutions and work with farmers to adapt them to their circumstances; (3) participatively select farms to become pilot projects; (4) participatively conduct a detailed farm survey and draw maps using CAD; (5) plan forest recovery, paddock layout, water locations, and forage enrichment; (6) participatively estimate and summarize economic impacts; (7) schedule implementation; (8) perform an on-farm project evaluation with the entire farmer family; (9) participatively implement the project; (10) conduct monthly tours of pilot farms with interested farmers; and (11) engage in participatory evaluation and reflection with the farmers, leading back to step one. Starting with a single farm adopting rotation grazing in 1998, by 2010, LASSre/UFSC had participated in 622 family farm projects [21]. Over time, it has become increasingly obvious that farmer livelihoods are integrally tied to the health of the Atlantic Forest Biome. Farmers have continued to work with us through dramatic changes in environmental policy, political regimes, and government support for our efforts as we describe below, though COVID dramatically slowed our work for several years.

PNS is used to tackle problems in which stakes are high, decisions are urgent, facts are uncertain, and values matter. The systems in which these problems occur are often unique, complex (e.g., a specific socio-ecological system or our single planet), and rapidly evolving (e.g., due to ecological degradation, technological innovation, or changing policies). What constitutes a solution depends on stakeholder values. PNS, like PAR, thus requires significant stakeholder input not only into the research process, but also into the evaluation of outcomes. In extended peer review, feedback from stakeholders is as important as that from scientists [36]. PNS is a theoretical complement to the PAR process described above and does not require any changes to the basic steps.

We note that ecological economists, agroecologists and restoration ecologists explicitly strive to change the systems they study to achieve specific normative goals. The theories of economists Smith, Ricardo, Mill, Marx, Marshall, and Keynes clearly did change the world [37]. In normal science, scientists observe a system to formulate objective hypotheses about how it works, then develop experiments to test those hypotheses. Many tests may

be required to support or reject a hypothesis. Under the conditions of PNS, there may be neither sufficient time nor sample size to engage in normal science. For example, one of the most important hypotheses guiding our research is that designing new agroecosystems and restoring sufficient forest cover in the Atlantic Forest can avoid system collapse. However, if restoration efforts prove successful, critics can claim that the biome was not under threat to begin with, and resources expended to preserve it were simply wasted [see [38] for more examples]). Modern science lacks methods for evaluating theories that change the system being studied.

Finally, much of our research on the small-scale impacts of our project on farmer livelihoods, biodiversity, microclimate, and soil chemistry is amenable to the methods of normal science, and appropriate methods are fully described in those studies cited here.

3. A Brief Description and Agricultural History of Our Case Study Site, Santa Rosa de Lima, and Methods

Santa Rosa de Lima is a small municipality (202,004 km², ~2130 inhabitants) in the Encosta da Serra Geral (coastal mountain slopes) of Santa Catarina in Southern Brazil (See Figure 1). The terrain is steep and rugged, thus ill-suited for large-scale mechanized agriculture. The landscape is dominated by family farms averaging 18 ha [39].

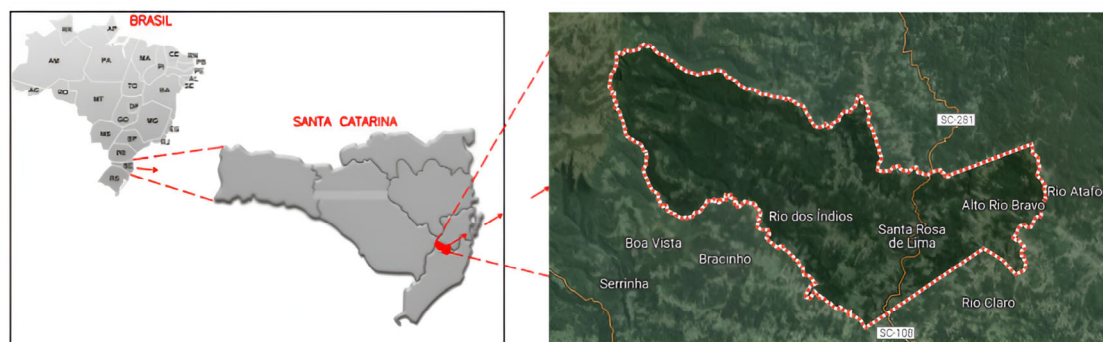


Figure 1. The study site: Santa Rosa de Lima, Santa Catarina, Brazil. Source: IBGE/Sirgas 2000 and Google Maps.

Slash and burn agriculture was introduced into the region at least 4000 years ago by the Tupi-Guarani, semi-nomadic horticulturalists, creating a mosaic of cleared land, second growth and natural forest [40–42]. Santa Rosa was invaded (settled) by primarily German immigrants around 1905, and the remaining Tupi-Guarani in the vicinity were exterminated shortly thereafter. Similar to the Guarani, colonists practiced diversified slash and burn agriculture for subsistence crops on family farms [43].

Industrial agriculture began to displace subsistence farming in the 1950s. Many farmers turned to logging, followed by exotic eucalyptus and pine plantations as remaining forests dwindled, and cash crops of hybrid corn, before shifting to input intensive tobacco farming in the mid-1960s. Tobacco had important advantages that led to its rapid dissemination. It offered higher returns on less land than other cash crops. Tobacco farming was easy to learn, especially with training and credit from tobacco companies, which targeted the most successful and respected farmers, and trained some to be extension agents. Tobacco companies provided a guaranteed market and a guaranteed price, dramatically reducing risk. By the end of the 1980s, most farmers in the municipality were growing tobacco while maintaining some of their traditional subsistence practices [43].

Despite its suitability to smallholder production, tobacco nonetheless exemplified many of the drawbacks of industrial agriculture. Tobacco quickly depleted the soil of nutrients, accelerated erosion, and forced farmers to purchase increasing quantities of fertilizers. Pesticide requirements had negative impacts on the environment and human health, including increased depression and suicide rates among tobacco farmers [44,45].

Falling tobacco prices in the 1980s further reduced farmer enthusiasm for the crop, forcing them to seek other alternatives [43].

In the late 1990s, the UFSC faculty (including co-author Schmitt-Filho) began working with local farmers on agroecological pasture-based dairy and organic vegetable production to restore the economic viability of local family farms. In collaboration with local, university-trained agronomists, farmers formed the “Associação dos Agricultores Agroecológicos da Encosta da Serra Geral—AGRECO” (<http://www.agreco.com.br> (accessed on 28 May 2024)), a small family farmer agroecological cooperative. Organic production earned premium prices, eliminated exposure to toxic chemicals, and had positive environmental and social connotations—clear advantages over tobacco. AGRECO helped lower adoption costs and increase returns by managing group organic certification and facilitating the marketing and development of local, artisanal, value-added enterprises. Side benefits included a surge in agro-tourism, leading farmers to organize an agrotourism cooperative—“Acolhida na Colônia” (welcomed by the community <http://acolhida.com.br> (accessed on 28 May 2024)) [46]. As other farmers become aware of the benefits, they too shifted to agroecological pasture-based dairy and organic vegetable production [43].

In 1998, agroecologist Schmitt-Filho and his research group, LASSre/UFSC, initiated a project with local dairy farmers using the transdisciplinary, participatory and action-oriented approach typical of agroecology [34].

In the case of our project, dairy farmers were attempting extensive grazing on land degraded by tobacco. They had low stocking rates, low yields, and worsening land degradation. They were looking for ways to improve their livelihoods and maintain the health of the land. LASSre proposed working with community farmers to implement and disseminate agroecological pasture-based dairy through rotational grazing, which divides pastures into numerous paddocks with electric fences and pumps water to paddocks, keeping cattle out of waterways [19,21,47]. Cattle are intensively grazed for short periods designed to maximize pasture growth rate. The process avoids selective overgrazing and pasture degradation, disrupts the life cycle of some parasites, and rehabilitates soil attributes degraded by tobacco farming. The ecological rehabilitation of pastureland was based mainly on management of stock density frequencies and intensities [47,48].

Farmers, however, were initially reluctant to adopt this unfamiliar practice. Conforming to the stereotype of innovators as venturesome and tolerant of risk and community rejection, one farmer with highly degraded land and little to lose adopted the practice in the face of overt skepticism and even ostracism from neighbors. Rotational grazing rapidly improved his pasture quality and stocking rate. LASSre/UFSC organized numerous field days and workshops to promote the practice, leading to widespread adoption by other farmers [19]. The practice proved so successful that it was turned into a state-wide government-supported program in 2006, and it is quickly becoming the standard approach to grazing in the state.

Organic and agroecological production had many of the same diffusion advantages as tobacco: economic and social benefits, compatibility with current practices, trialability and observability. Access to University experts and cooperative associations helped overcome the challenge of greater complexity [19]. But the diffusion of agroecological practices also confronts challenges. The ex-situ ecosystem services enhanced by agroecological farmers and degraded by conventional farmers are difficult to observe and rarely affect farmer income. Organic certification is expensive—an example of the perverse non-polluter pays principle—and group certification is risky, since non-compliance by a single farmer can void certification for all, as happened to the Geração Organic Dairy Cooperative when a clandestine conventional tobacco crop was discovered in one farm. Furthermore, salespeople from private firms promote the use of fertilizers and pesticides. As a result, many dairy farmers abandoned organic production, though they continued with rotational grazing [28,49]. While organic agriculture and rotational grazing may reduce ecological impacts, they do little to actively restore degraded forest systems or avoid ecological collapse. More is needed.

4. Scientific Considerations: Designing Restorative Agroecosystems

Agronomists and economists frequently extol the efficiency of industrial agriculture, which produces more food per acre and per farmer than any alternative. Agroecologists and ecological economists, however, recognize that through thermodynamic, ecological, and human-needs lenses, it is among the least efficient agricultural systems in history. Thermodynamically, industrial agriculture converts an estimated 10 calories of hydrocarbons into 1 calorie of food on a plate [50,51]; ecologically, it threatens planetary boundaries; in terms of human needs, it focuses on grain crops used largely to provide animal protein for the wealthy and cheap, unhealthy processed foods for the poor. The goal of food systems should not be to maximize food production, but rather to provide food security for all. Restorative agriculture must achieve this while actively rehabilitating the agroecosystems degraded by conventional agriculture. This means producing the right foods (allocative efficiency) and ensuring they go to those who need them most (distributional efficiency), producing as much food as possible from a given level of throughputs, defined as resource inputs and their waste outputs (technical efficiency), and minimizing the ecological harm caused by those throughputs (ecological efficiency) (adapted from Daly's ecological economic efficiency identity [52]).

Agroecology is a science, practice and movement dedicated to these goals. As a science, agroecology applies insights from ecology to agriculture, with the goal of creating an agriculture system that exists in harmony with surrounding ecosystems. As a practice, agroecology emphasizes freely shared local knowledge developed through participatory action research, in which farmers work with scientists on the co-creation of knowledge that meets the needs of farmers and their communities [34,35]. It seeks to minimize the use of off-farm inputs (e.g., the fertilizers and pesticides threatening planetary boundaries) and increase system diversity and resilience. As a movement, agroecology seeks to build a restorative agriculture system at a global scale and correct the unjust distribution of political and economic power that imposes poverty on the most essential workers in the most essential economic sector [53]. Numerous studies show that locally adapted agroecological practices can significantly increase yields, decrease costs, conserve resources, improve ecosystem health and restore ecosystem services on small family farms, while reducing agrochemicals and negative ecological impacts [54–59].

While organic horticulture and pasture-based dairy in Santa Rosa offer significant environmental advantages over input intensive agriculture, they do not restore forest cover, and hence may do little to avoid ecological collapse. Though forbidden by Brazil's 2006 Atlantic Forest Law, our research shows that deforestation reduced native forest cover from 72% in 2002 to 51% in 2010 in Santa Rosa, as the Eucalyptus plantation area increased from 2.7% to 24.8% [60,61]. In response to this, and to the Brazilian Forest Code's legal mandate to reforest described below, we have worked with forestry experts, farmers, NGOs (e.g., AGRECO, EPAGRI) and other stakeholders to design and implement High-Biodiversity Silvopastoral Systems (SPSnu) and Multi-Functional Riparian Forests (MultRF) (which we will refer to jointly as SPSnu-RF) to restore rural landscapes, ecosystem functions and services, increase food production, improve farmer livelihoods, and comply with the law. Farmer input into the design of agroecosystems is critical, since they are the protagonists who decide whether to adopt a new technology. The use of applied nucleation in degraded agricultural lands is a new approach to ecological restoration [29].

SPSnu consist of 5×5 m plots of native agroforest integrated into treeless, rotationally grazed pastureland at roughly 40 nuclei per ha. Our approach is based on functional diversity [62,63] to accelerate ecological restoration through successional processes. Selecting species for both ecological and economic benefits, we utilize the strategy of applied nucleation, with small clumps of trees mimicking natural succession as a cost-effective restoration technique [64]. Our plantings consist of five functional groups (FGs). FG1 is provisioning services with pioneers (including bananas, the only exotic species), focused on achieving canopy cover and the production of quick market benefits. FG2 is landscape restructuring/succession facilitation, consisting of fast-growing pioneer species that can

rapidly create the conditions necessary for other native species to thrive. FG3 is provisioning services with keystone species, prioritizing the Juçara Palm (*Euterpe edulis*), a close relative of açai (*E. oleraceae*) with high market value. Trials of *E. edulis* agroforestry systems with 625–1000 trees per hectare in nearby regions suggest internal rates of return (IRR) of 21% to 67.5% [65]. FG4 is enrichment, achieved by adding two late secondary and climax trees to enhance biodiversity. FG5 is pollinators, consisting of native bee hives, whose honey is also a valuable market product. We strive for 60 different native species per hectare.

The functional groups are planted over the course of 3–4 years. The SPSnu cover 10% of pastureland, and within two years provide shade cover over ~30%, alleviating heat stress, which in sub-tropical ecosystems can reduce milk production by as much as 20% [66–68]. Many farmers have stated their willingness to adopt SPSnu for shade cover alone [69]. The result is 40 SPSnu per hectare with 320 *E. edulis*, 160 bananas, and eight hives of native bees. Bananas and some pioneer species start producing crops during the second year. *E. edulis* takes five to seven years to begin fruiting.

The MultRF includes the same five functional groups of native species as the SPSnu, with a minimum of 8 m-wide strips on either side of waterways designed to comply with Brazil's New Forestry Code, discussed below. In addition to the ecological benefits of SPSnu, MultRF provides ecological corridors across farms, water regulation and purification, and appears to reduce populations of “borrachudos”, biting black flies that torment farmers, cattle, and researchers. Our long-term goal is to design profitable riparian buffers, thus increasing the likelihood of achieving sufficient forest cover to avoid the collapse of the Atlantic Forest Biome [25,70,71].

To evaluate the success of rotational grazing and SPS-RF, we work with farmers, university students, and disciplinary experts to collect baseline data and monitor impacts on ecosystem services and farmer livelihoods as they co-evolve within a dynamic socio-ecological system [72].

To assess impacts on farmer livelihoods, we sampled 61 farmers from four dairy cooperatives who had transitioned from extensive to rotational grazing. Farmers estimated an average 67% increase in milk cows (heads), a 104.5% increase in young stock (heads), a 28.6% increase in milk per head, and a 128.6% increase in income [49]. A subsequent economic study comparing 15 farms using rotational grazing with 12 using conventional grazing systems found that the former had significantly higher revenue (USD 199 vs. 124/ha/month), gross profits (USD 109 vs. 68/ha/month), gross return on assets (10% vs. 6%) and net return on assets (1% vs. −2%) than the latter [73]. We have yet to conduct economic assessments of SPS-RF systems.

We also measured positive impacts on ecosystem services. Farmers perceived that rotational grazing improved soil health and biodiversity [49,73], and farmers engaged in rotational grazing were significantly better informed about ecosystem services than conventional farmers [74,75]. We assessed the impacts of SPSnu on microclimate, pasture production, and pasture chemical composition, microclimate and biodiversity as compared to treeless pastures. We found lower air and soil surface temperatures in pastures shaded by SPSnu, with a maximum difference of 4.3 °C and 5.2 °C, respectively, during spring and summer, suggesting the SPSnu are useful for climate change mitigation and adaptation [67]. However, SPSnu can also reduce wind speed, and when trees are too small to provide abundance shade, this can increase the heat load index for cattle [76]. Pasture growth was fastest in areas between the SPSnu in every season, and slowest in the TP in winter. The dry weight of pasture was also highest in pastures shaded by SPSnu, as was summer protein content, with insignificant differences for other seasons [77].

We measured forage biomass in treeless pastures, shaded areas near SPSnu, and shadeless areas between nuclei, and found that pastures with SPSnu produce as much forage with the same carbon and nitrogen content as treeless pastures, despite a 10% loss of pasture to SPSnu and increased shade [78]. A separate study found that cows spend more than half their grazing time and nearly 2/3 of all time in the shade [66]. A separate study

found that 97% of 60 farmers interviewed were aware that silvopastoral systems could reduce productivity losses to temperature extremes [74].

We also compared soil structure in treeless pastures under rotational grazing, SPSnu, secondary forest and primary forest. Soil density was greater in the first three than in primary forest, but still low enough to permit root development. The SPSnu and rotational grazing pastures, however, had greater aggregate size and aggregate stability (indicators of soil health) than primary forest, indicating their ability to improve soil health [79].

To assess impacts on bird diversity, we identified bird calls from sound recordings in treeless pastures (TP), SPSnu, forest edges and forest interiors on three different. On average, we found significantly higher avian species diversity in SPSnu (34 sp.) than TP (27 sp.), though both had significantly fewer species than forest interiors (45 sp.) and forest edges (34 sp.).

The PAR process influences not only what is studied, but also what happens to the resulting knowledge. Knowledge improves through use [80]. Intellectual property rights deter innovation [81] and decrease the value of existing knowledge by limiting access to those who can afford it [82]. Close interaction between extension, professors, students, and farmers and the ongoing monitoring of results facilitates continual innovations that improve both economic and ecological benefits. The resulting knowledge is a public good freely available to all and intended to spread from farmer to farmer, in marked contrast to the largely proprietary technology of industrial agriculture. Open access publications (including over 25 cited in our references), student theses, and online videos (e.g., <https://www.youtube.com/watch?v=KM7XVRhuVjM> (accessed 28 May 2024)) also make results accessible to the broader research community. However, it is not scientific peer review but extended peer review—the willingness of farmers to adopt specific practices—that measures the value of our project.

Our research offers several key lessons we believe are widely applicable to the science of ecological restoration and rehabilitation of agroecosystems. First, scientists trained in single disciplines are likely to focus on only a small subset of relevant costs and benefits. While this reductionist approach can be extremely useful, it is a major reason that conventional food systems fail to feed the hungry while causing potentially catastrophic harm to ecosystems. Transdisciplinary research integrating local knowledge improves our understanding of benefits and costs, hence efficiency. Second, our knowledge of agroecology and human impacts on the environment is increasing rapidly, so developing restorative agroecosystems must be an ongoing process. Third, any technologies that contribute to ecological rehabilitation of agricultural lands will be more valuable if they are free, but the ultimate judge of value must be the farmer who decides whether to adopt an innovation. Fourth, new technologies alone are insufficient to redesign agriculture, as we explain in the remainder of this article, beginning with a discussion of economic and social challenges to disseminating restorative agriculture at scale.

5. Social and Economic Considerations: Disseminating Innovation

There are many good economic and social reasons farmers may be resistant to adopting more sustainable agricultural practices. Dissemination of Innovation Theory (DOIT) identifies five characteristics of innovation relevant to the rate of adoption: Relative advantage (is it better than alternatives?), Compatibility (is it consistent with the values, experiences and goals of farmers?), Trialability (can it be adopted on a limited basis?), Observability (are the results obvious?) and Complexity (how easy is the innovation to learn?).

We note that much of the DOIT literature has focused on the diffusion of industrial agricultural technologies. Industrial agriculture relies on top-down knowledge in the form of external inputs and practices that are very similar across farms and regions and focuses primarily on economic benefits. In contrast, the integration of agroecology and ecological rehabilitation is typically site-specific, which requires adaptation to different socio-ecological systems and continual innovation, rather than simple adoption. Local stakeholders are likely driven by multiple and potentially conflicting goals, including

farmer health, food quality, social and environmental impacts, soil rehabilitation, animal welfare, and biodiversity, in addition to economic benefits [34,83]. Fortunately, PAR can help us tailor DOIT to the ecological rehabilitation of agroecosystems.

The farmers we work with identified economic returns, time, labor, and risk as some of the most important elements of relative advantage. As detailed in the previous section, we have documented improvements in farmer livelihoods and ecosystem services from rotational grazing. Our unpublished preliminary assessments suggest that SPSnu-RF could offer rates of return as high as 57% and contribute to diversification, theoretically reducing risk, but it will be several years before we have enough farmers practicing SPSnu-RF for a long enough time to make trustworthy estimates of economic returns. Uncertain future benefits must be balanced against the immediate time and labor costs of fencing off and planting SPSnu-RF. Furthermore, the continuous R&D inherent to agroecological practices improves outcomes over time, which may make delayed adoption more rational for the individual, even when rapid adoption is better for society. Adopting new innovations unavoidably adds to the notoriously high risks of farming, especially when farmers lack adequate knowledge about the effectiveness of the innovation or how to apply it.

Two other challenges undermine the relative advantage of SPSnu-RF. First, Brazil's notoriously high interest rates [84] penalize practices with high up-front costs and delayed returns. Perhaps most important, many of the expected benefits are public goods in the form of ecosystem services, whose values flow to society as a whole. No matter how valuable their benefits, off-site ecosystem services offer no relative advantage in the absence of compensation for their provision.

Compatibility with conventional practices is reasonably high, since many farms already include Eucalyptus stands, and SPSnu-RF would help farmers comply with Brazil's New Forest Code, discussed below. On the other hand, there is also a social element to compatibility. Farming communities can be quite conservative. As previously mentioned, the first farmer in Santa Rosa de Lima to adopt rotational grazing initially faced social ostracization.

Trialability and observability are mixed. Farmers can easily adopt SPSnu-RF on small portions of their land and can easily observe the cattle's preference for shade. However, the impact of shade on milk production is more difficult to observe, and it may take years before returns to non-timber forest products (NTFP) are significant. On-site ecosystem services such as provision of soil carbon sequestration, nutrient cycling, and biological pest control, as well as greater biodiversity and system resilience, are not always obvious. Off-site ecosystem services are even harder to observe, and preventing the collapse of the ecosystem would be counterfactual, hence unobservable. Complexity is also a serious challenge, since agroecology in general is knowledge-intensive and refined through trial and error. Managing tree crops in addition to dairy cows is certainly more complex than simply managing the latter. Such obstacles can slow diffusion [83].

Despite these challenges, the first five innovators in Santa Rosa de Lima began adopting SPSnu in 2012–2013, and MultRF a year later, albeit with many of the implementation costs covered by the LASSre/UFSC team and the local government. These innovators are well integrated into the community, their opinions are respected, and they are well connected with a variety of information sources, including university professors and extension agents—characteristics of early adopters known to accelerate diffusion. Numerous additional farmers have expressed interest in adoption, though they are typically unwilling to cover initial costs on their own. DOIT suggests that once 10–20% of a community has adopted a practice, diffusion can become self-sustaining [83,85], which is supported by our experience with rotational grazing.

There is also a five-step process for each individual involved in adoption. The first step is knowledge about the innovation, which might come from personal experience, peers, media, and/or extension agents. Three types of knowledge are important: awareness that an innovation exists, an understanding of how to implement it, and an understanding of the principles that make it work. Our first adopters have made this knowledge more

available. The second step is persuasion, the forming of positive or negative views of the technology, which is strongly affected by the characteristics of innovations described above, as well as the opinions of others with whom the farmer communicates. Next comes the decision stage, when the farmer decides whether to adopt the technology (perhaps with adaptations to the local socio-ecological system), the implementation stage, where advice from peers or extension agents can again be useful, and finally the confirmation stage, when the adopter decides to continue with the innovation or abandon it [85]. In the context of agroecology, innovation is a dynamic process, with continual adaptation.

We emphasize three key lessons from our research on the social and economic aspects of the transition to restorative agriculture. First, adopting new technologies is always risky, no matter how promising they appear, and farmers have good reasons to be risk-averse. The DOIT literature offers many lessons for speeding up innovation, including the need to work with respected community members. Second, high interest rates can increase these risks, especially when costs are immediate, and benefits delayed. Third, many of the benefits of restorative agriculture are public goods, and small family farmers cannot afford to risk their personal welfare to provide public benefits. We therefore turn next to the role of the state in promoting sustainable agriculture.

6. Political Considerations: State Support for Restorative Agriculture

A restorative agricultural economy must be sustainable, just and efficient. No single policy is likely to achieve all these goals, and policies designed to achieve one goal may often conflict with other goals; it may therefore be necessary to implement additional policies to counteract or reverse these unintended affects [86,87]. This section explains how Brazil's Forest Code (BFC), focused primarily on ecological sustainability, conflicts with the goal of a socially just distribution, which led to enacting a new forest code in 2012 that requires less reforestation but has a greater chance of being enforced. We then discuss the need for more Research and Development funding for agroecology and ecological restoration, our efforts to pursue this, and the setbacks caused by political change. Finally, we present our efforts to develop more socially just policies that will facilitate enforcement of the weaker New Forest Code (NFC), while improving farmer livelihoods. We approached various government agencies to discuss options, and while many were enthusiastic about our project, we have not yet been able to turn this enthusiasm into policy. We outline our current efforts to develop a modified payment for ecosystem services (PES) scheme with the State Secretariat of Agriculture. The most just and efficient policies would require all who benefit from the restoration of the Atlantic Forests, including other countries, to contribute proportionately to the costs of restoration, which is the goal of PES. We have discussed international PES mechanisms elsewhere [88], and focus here on state policies to support restorative agriculture.

6.1. Allocating Land between Agriculture and Ecosystems: Brazil's New Forest Code

Brazil's Forest Code (BFC), created in 1965 (with numerous subsequent modifications), prescribes native forest cover on ecologically sensitive lands (riparian zones, around springs, on steep hillsides and on hilltops) known as Areas of Permanent Preservation (APP) and in a Legal Reserve (LR) consisting of 20% of Atlantic Forest Properties outside the APP [89]. Prior to 2012, compliance with the forest code would have ensured about 30% forest cover [70], but the law threatened small farmer livelihoods and consequently went largely unenforced. Driven by the apparent conflict between the BFC and farmer livelihoods, the Brazilian government passed a New Forest Code (NFC) in 2012, which reduced the size of the APP for small family farmers and offered an amnesty for deforestation that took place prior to July 2008. This reduced reforestation requirements by about 57% for the Atlantic Forest as a whole, and by 88% in Santa Catarina [89]. Reforestation requirements are no longer sufficient to ensure 30% forest cover. Our analysis suggests that these revisions favor commodity expansion over the provision of other ecosystem services, and could lead to fewer farmers adopting more sustainable practices [90]. On the other hand, the NFC also

allows agroforestry systems and NTFPs in the APP and RL for family farmers [91], which benefits our project.

As part of the NFC, farmers are required to prepare a rural environmental registry (Portuguese acronym: CAR) that maps current land use, areas that must remain forested, and those which must be reforested. Farmers must then develop and implement a Program for Environmental Regularization (Portuguese acronym: PRA), designed to help bring them into compliance with the law [89]. The NFC has also created tradable property rights to the RL in the form of environmental reserve quotas (ERQ) (ERQs were actually allowed under the BFC, but only within the same watershed; furthermore, since the BFC was not enforced, there was little incentive to use the mechanism). Previously, each Atlantic Forest property had to maintain a 20% legal reserve, regardless of the economic value of the land. With the ERQ, farmers who have less than 20% land cover in RL can pay other farmers with excess RL, then count that area towards their own RL without purchasing the property outright. This policy allows farmers with high opportunity costs for RLs to maintain their agricultural land, while rewarding those who have preserved or restored their forests. Furthermore, if the NFC is enforced, and penalties imposed for those who do not comply, it would create an important advantage for SPSnu-RF relative to conventional agriculture.

We used graphical information systems (GIS) to delimit the APP in Santa Rosa, and found that they cover just over 50% of the municipality, with 76% already in forest cover [92]. Adopting RFmult in the appropriate areas would help farmers comply with law, while adopting SPSnu would allow some farmers to sell ERQs. Though the NFC requires the State to help the farmers comply with the law, few states have done so. As part of our project, we favor two promising options.

6.2. Subsidies for Agroecology R&D

One of the most important policies for developing restorative agriculture is public support for scientific research, development and extension. As one noted Brazilian scientist titled an article in *Nature*, “To save Brazil’s rainforest, boost its science” [93]. Increased research, development, and extension are essential to increase food production and reduce environmental impacts [94,95]. Public sector investments in agricultural R&D offer exceptionally high rates of economic returns, often exceeding 50% [96–98]. The Brazilian Agricultural Research Corporation (EMBRAPA) generated an estimated internal rate of return of 38.2% in 2016 [99]. However, these estimated returns ignore ecological costs. Brazil is the world leader in pesticide use, including many banned in other countries, and accounts for 20% of global consumption [100]. On the other hand, Brazil has also had significant success integrating crops, livestock and forestry systems, with positive social, environmental and economic benefits (or combinations thereof) [101]. Accounting for environmental benefits would favor integrated agroecosystems over conventional agriculture. High returns on agricultural R&D and extension indicate more investments are desirable [94,95], and more accurate accounting of ecological costs when estimating returns would favor greater investments in agroecology [18,102].

R&D for industrial agriculture imposes an additional challenge to restorative agriculture: it increases agricultural profits, land values and the opportunity cost of conservation. A preliminary analysis by EMBRAPA suggests that R&D significantly contributed to the 250% increase in agricultural land values from 1992 to 2015 [101]. While farmers are now able to produce much more food per hectare, industrial farmers must also forgo more income from land in forest cover. In contrast, R&D in agroecology practices such as SPSnu-RF could reduce or eliminate these opportunity costs. Furthermore, the paucity of R&D in agroecology relative to industrial agriculture suggests that marginal returns to investments in the former are likely to be higher [102,103].

The Brazilian Federal government pays the salaries of the LASSre team at UFSC, thus contributing to R&D in agroecology, though funding for agroecology R&D has never been sufficient to counteract the impacts of Brazil’s significant R&D expenditures for industrial agriculture. Unfortunately, our project suffered setbacks when the Bolsonaro government

slashed funding for scientific research [104] while giving full support to Brazil's global agribusiness [105]. While scientists are optimistic that the return of President Lula will reverse this trend, the pace of change has been slow [106]. Our team must therefore pursue other options as well.

6.3. Subsidies for Ecosystem Services

In Brazil and many other countries, conventional farmers pay a negligible share of the off-site ecological costs of their practices, while agroecological farmers receive a negligible share of the off-site ecological benefits, distorting the relative advantage for farmers in favor of conventional farming. Either payments for sustainable farming practices or penalties for unsustainable ones can provide economic incentives for restorative agriculture. However, policies that force farmers to internalize the ecological costs of farming could significantly increase food prices, with unacceptable impacts on the poor [107]. In contrast, public payments for ecosystem services for agroecology could increase its relative advantage without raising food prices.

Payments for ecosystem services (PES) have become increasingly popular in Brazil over the past decade and have recently been implemented in Santa Catarina. In 2021, Brazil initiated a national PES program. There is a vigorous debate about the effectiveness of PES [108–112], but the underlying rationale is simple. Many ecosystem services are public goods generated on private land. Government PES is simply a transfer of government resources to landowners as an incentive for adopting land uses that generate ecosystem services, or to compensate them for the opportunity costs involved, in theory bringing individual land use decisions into better alignment with the social interest [113].

The pioneering Conservador de Aguas program in the city of Extrema, Minas Gerais, provides an example. It began in 2005 with the goal of improving water quality in the city of Extrema by replacing cattle pasture in riparian zones of the Rio Jaguari watershed with forest cover. Under the program, farmers are paid the approximate opportunity cost of pasture for restoring and conserving forest cover in their APPs, registering the Legal Reserve, managing erosion, and providing on-farm waste-water treatment. The municipality, with critical assistance from universities and non-governmental organizations, manages restoration activities. Enrolling farmers proved the most challenging part of the project, but was facilitated by explicit threats of enforcing the BFC. The program prioritizes the recruitment of influential farmers to speed diffusion [23,114].

Other useful lessons come from the Regional Integrated Silvopastoral Ecosystem Management Project (RISEMP), a pilot project conducted in micro-watersheds in Costa Rica, Nicaragua and Colombia, designed as a randomized control trial to test the effectiveness of temporary PES and technical assistance in incentivizing farmers to adopt silvopastoral systems designed to restore degraded pasture, sequester carbon and increase biodiversity. Over time, virtually all farmers studied, including the control groups who received no payments, adopted many of the practices and continued them even after payments ended [115]. Communications between farmers and neighbors, farm visits, and community presentations on agriculture were found to be more influential than communication with extension agents [58]. On the whole, it appears that the program played a critical role in promoting diffusion, partly by helping farmers manage the initial transition costs but mostly by increasing observability and information flows.

Banks-Leite, et al. [25] estimate that in Brazil, by combining PES (at USD 134/ha, the average for PES programs in the biome, significantly less than the average opportunity cost of USD 467/ha) with the significantly higher costs of active restoration where necessary (~USD 5000/ha over three years), it would be possible to achieve 30% forest cover in priority landscapes for only 6.5% of Brazil's current budget for agricultural subsidies. Presumably, such payments would need to be continued indefinitely, especially in areas where reforestation is not required by the NFC.

PES suffers from many shortcomings. High transaction and monitoring costs make it difficult to target small farmers, and proving additionality and effectiveness is difficult [108].

Recurring economic crises and faltering political will can threaten continuity. Rising food prices—expected to continue as a result of climate change, population growth, and other factors [116]—can undermine PES by increasing opportunity costs, as happened when a surge in corn prices led to a 30% decrease in land enrolled in the US Conservation Reserve Program [117]. Monetary payments may crowd out intrinsic motivations to protect ecosystems [118–122]. Finally, PES schemes focused only on conservation compete with agricultural land. Scaling up PES programs to the level required to protect threatened global ecosystems could reduce global food production, leading to skyrocketing prices, causing tremendous hardship for the poor [107].

Despite potential shortcomings, PES is a pragmatic choice in a country where it has become an accepted policy instrument with broad state support. Together with farmers, local government, and the Santa Catarina ministry of agriculture, we are applying the principles of PAR to develop a pilot PES program to promote the adoption of SPSnu-RF. A key demand of participating farmers is that the agroecological innovations offer a relative advantage over alternative practices in terms of risk, labor demands, and livelihoods. The major obstacle to the adoption of SPSnu-RF is implementation costs, including labor, and the long time-lag before NTFPs begin producing. The farmers are most interested in policies that finance the initial costs of adoption and share the risks of failure. We view this approach as a co-investment in land stewardship to achieve shared goals rather than market payments conditional upon service provision.

We are currently working with the State Secretariat of Agriculture to develop a pilot PES project across a small watershed that will showcase the benefits of SPSnu-RF for both farmers and ecosystems. Acknowledging that expected benefits consist of both public and private goods, the state would provide subsidized loans to the farmers to cover implementation costs, including labor. Conditional upon adoption of these practices, loans would be interest free, with payments deferred until the agroecosystem shows increased profitability, which we estimate will take five to eight years. Farmers who maintain these agroecosystems will pay back only a share of the loans contingent upon increased revenues. LASSre will continue to provide extension support and conduct empirical research on the project outcomes. Since farmers receive the payments up front, they are unlikely to abandon the agroecosystems if the policy is canceled in the future. We are also exploring the option of a revolving loan fund (RLF), in which repayments (contingent upon profitability of the SPSnu-RF) would be loaned out to subsequent cohorts of farmers. RLFs have been successfully used elsewhere to finance green infrastructure, water quality, and enterprise expansion on small organic farms [123]. We expect that farmers will view the policy as government assistance to achieve shared goals, which we hope will strengthen any intrinsic motivation of farmers to manage their land for the common good. Because farmers can produce both food and ecosystem services on the same land, they are less likely to abandon the system when food prices rise.

Perhaps not surprisingly, the policy-makers with whom we have been speaking appear less interested in the results of our quantitative research on the ecological and economic impacts of SPSnu-RF than in our qualitative descriptions of the project and the political optics of our policy proposals. This is not entirely a bad thing. In a highly complex, rapidly changing world, we should not put too much trust in precise quantification. Mainstream agronomists and ecologists can provide convincing quantitative evidence that their approaches are the best for achieving their specific goals, but if their goals are poorly chosen or incomplete, that evidence is of limited use. We cannot be certain that the agroecosystems we are designing are the best approach to restoring degraded ecosystems while improving farmer livelihoods, and view agroecosystem design as an adaptive process with no single best outcome. Our approach is to continually assess the ability of our project to improve farmer livelihoods and ecosystem health, improve the project elements that achieve this, and replace those that do not with new experiments in an ongoing process. In this dynamic approach, the right goals are more important than the specific practices with which we are experimenting.

We offer what we hope are three generic lessons from our work on politics and policy. First, policies intended to restore rural ecosystems may have disproportionate impacts on farmers. For policies to be successful, they must be enforced, but enforcement is unlikely if important political constituents are harmed. The answer is not to abandon pro-environment policies, but rather to supplement them with additional policies to address distribution or other goals. Second, it is important to be pragmatic. Policies must be acceptable to both farmers and policy-makers. If there are political obstacles to necessary policies at the national level, researcher-advocates should look to state and local governments for options. Rather than pursuing the ideal policy, it may be necessary to work with policy-makers to tailor existing policies to the goal of creating a restorative economy. Third, we should abandon the idea that the job of scientists is simply to present objective facts on the assumption that politicians will respond accordingly. Science is less objective than we pretend. Scientists often measure what matters to their discipline, which is not necessarily that same thing that matters to policy-makers and other stakeholders. Effective narratives and the right goals may be more effective at swaying policy-makers than quantitative “facts”.

One conclusion we have reached based on our research is that science, economics and politics may be insufficient, even collectively, to develop restorative agriculture at the scale needed. We believe a change in morality is required.

7. Ethical Considerations: Changing Relationships to Land, Society and Nature

While our project has made significant progress towards developing restorative agroecosystems, we agree with Becker that developing a sustainable economy requires a change in moral and ethical values. We draw on theories of multi-level selection and cultural evolution to support this assertion.

The secret to human success is our unprecedented ability to evolve social norms—morals and ethics—that allow us to cooperate at larger and larger scales [124,125]. There are three necessary and sufficient conditions for natural selection to occur: heritability, variation, and differential survival. Moral values clearly vary across individuals and cultures and have a profound impact on survival—society could not exist without moral values, and humans are incapable of surviving apart from society. While physical traits evolve primarily through genetic inheritance, human cultures evolve through symbolic evolution, our ability to pass on abstract ideas through writing and language. Moral values are passed on through cultures, but can also be intentionally modified [126], as happened with moral values concerning slavery, racism, sexism, and the like.

Anthropologists have identified cooperation as the most universal moral value [127]. Cooperation means putting the interests of the group ahead of the interests of the individual. Cooperation is the only solution to social dilemmas—“situation[s] in which members of a group can gain by cooperating, but cooperation is costly, so each individual does better personally by not cooperating, no matter what the others do” [128]. Our ancestors faced innumerable social dilemmas—hunting large game, defending the group against enemies, building irrigation systems, and so on—and those groups best able to cooperate left more descendants than more selfish groups. While many species have evolved a genetic capacity for cooperation, in humans in particular, this has been significantly enhanced by cultural evolution [129].

Helping someone who does not help you or your kin in return reduces individual fitness [130]. Reciprocity is therefore central to the evolution of cooperation, and so important in this regard that many cultures regard it as ontological, part of the nature of being [131,132]. In economic systems based on reciprocity, those with an abundance of resources share them with those who have less, who then feel a moral obligation to reciprocate in the future. In this way, each economic exchange strengthens social ties. Tracking reciprocity requires considerable brain power. Primate group size strongly correlates with brain size. Based solely on the size of our brain, humans are capable of tracking reciprocity in groups of about 200 [133]. Culture, however, has generated mechanisms for increasing

cooperation and punishing selfishness, thus facilitating cooperation at larger and larger scales [124,125]. Money appears to have evolved into a social construct that immediately tracks reciprocity, allowing us to cooperate with people we neither know nor trust. In economic systems based on money, economic exchange is typically finalized with each encounter and builds no further social relationships. Mere exposure to money or to market framing is correlated with more self-interested behavior [134,135]. Money appears to act as a supernormal stimulus, eliciting a stronger response than the reciprocity and social connection stimuli it has come to replace [136].

Multi-level selection theorists recognize that natural selection can take place at the level of the group or the individual. The most selfish individual outcompetes other individuals within a group, but the most cooperative and altruistic groups outcompete other groups. In a handful of species, including humans, natural selection acts most strongly at the group level [137]. In humans, group-level selection is primarily cultural [138].

The definitions of individual and group change with scale and with evolution. A major evolutionary transition occurs when an organism formerly capable of replication on its own becomes so dependent on a group it can only replicate as a collective. Cooperating bacteria and archaea merged into the eukaryotic cell. Single cellular eukaryotes merged into multicellular ones. Individual animals became social animals [139]. A human cannot survive independent from society any better than a human cell can survive independent from the body [140]. Individual species form ecosystems that generate life support functions essential to all species [141]. All of this depends on cooperation—the individual putting the interests of the group ahead of its own. Failure to do so harms the larger group. The cell focused solely on its own reproduction is cancerous. The purely self-interested individual is a sociopath. The species focused solely on its own reproduction becomes a plague [15,142].

The market economy is driven by private property rights, self-interest, and individual choice. It is explicitly dedicated to the satisfaction of subjective individual preferences. In essence, it is an egocentric economic institution aligned with individual-level selection, hence ill-suited to solving social dilemmas. The public purpose sector, including government, NGOs, and civil society, is ideally driven by collective preferences and collective choice. Contributions to the collective, ranging from military duty to obeying the law, are often framed as ethical obligations to promote the common good. In essence, the public purpose sector is a collection of group-centric economic institutions aligned with group-level selection. International institutions such as the IPCC and IPBES seek to build anthropocentric economic institutions focused on all of humanity.

Over the past 200 years, the human population and economy have grown exponentially, with little concern for the ecosystems that sustain us. Descartes, the embodiment of the Enlightenment era, distinguished between body and soul, matter and mind: apart from humans, nature is a collection of objects, animated machinery with no moral standing, free for humans to use as we like [143]. Following this philosophy, humans have become equivalent to geological forces in shaping planetary ecosystems. We are altering the climate, driving mass extinction, and generally threatening the ecological life support functions on which all species depend [144]. Western society marvels at its own adaptive fitness as it displaces more “primitive” groups. But evolutionary fitness must be measured over time. Western culture has created unprecedented threats to global ecosystems in only 200 years, while many existing cultures have survived for millennia. One seemingly universal attribute of these surviving cultures is their recognition that they are part of the larger ecosystems that sustain them. They feel moral obligations to reciprocate for the gifts they receive, and to take only what is necessary [145–147]. In our view, this is not because indigenous peoples are somehow smarter, wiser, or inherently more sustainable, but rather because those cultures that prioritized their own needs over the ecosystems that sustained them went extinct. Sustainability requires ecocentric economic institutions aligned with ecosystem level selection; economic institutions aligned with individual self-interest cannot work.

In distinct contrast to the Anthropocene Era, Thomas Berry has called for the intentional evolution of an ecozoic era characterized by mutual flourishing between humans and the rest of nature [148]. We must learn to understand natural systems as a communion of subjects with moral standing, not a collection of objects with mere instrumental value measurable in monetary units. Nature has bestowed invaluable gifts upon us, and we must reciprocate by taking from nature only what we need and by restoring degraded ecosystems, which is to say, by building a restorative economy. It is time to shift our focus from nature's benefits to people (the standard definition for ecosystem services) to people's benefits to nature.

We must also understand human societies as a communion of subjects. In modern society, no individual in a lifetime of study could master all the technologies required to produce a single meal or single item of clothing. The culture we depend on for our survival is cumulative and collective, created by billions of people over thousands of years [140,149]. If we are to build a restorative economy, we must change our ethical relationships to land, society and nature. We must recognize that humans have undergone a major evolutionary transition. In our globally interconnected society, we depend on people from all nations. We must prioritize the welfare of humanity over the welfare of the individual in the same way our cells prioritize the welfare of the body over their own unrestricted replication.

Land is a shared gift from nature. Disseminating restorative agriculture at the necessary scale may only be possible if we intentionally evolve a moral obligation to manage land for the benefit of society and nature, not for private gain.

8. Summary and Conclusions

Our myriad ecological crises attest to the need for the urgent development of a restorative economy. Since agriculture is the most important economic sector and the greatest threat to global ecosystems, we focus on the challenges of developing a restorative agricultural economy. We have used a case study of the challenges confronting the dissemination of perennial-dominant agroecology among small family farmers in Brazil's Atlantic Forest to illustrate some of these challenges. We are applying the methods of Participatory Action Research and Post Normal Science to integrate the goals, knowledge and values of the stakeholder community, and adapt to ongoing environmental, economic and political changes. Key lessons include the need for transdisciplinary approaches not only in the technical design of restorative agroecosystems, but also when confronting social, economic and political obstacles to their adoption.

On the science side, many of the existing problems with our agricultural system arose because agronomists were unaware of the ecological impacts of their technologies, while ecologists have historically focused on restoring systems to their natural state, free of human influence, which is no longer a possibility. Both sides often paid too little attention to local needs and values. While interdisciplinary collaboration between agronomists, and ecologists would likely result in better technological designs than each working alone, their differing world views may make collaboration difficult. Agroecologists and ecological economists, in contrast, are transdisciplinary, trained to take a systems perspective and to account for the goals, values and knowledge of various stakeholders. Participatory action research ensures continual feedback from stakeholders and continual improvements to any technologies developed. Importantly, it also ensures those technologies will be freely available to all who wish to use them.

Turning to the social, economic and political aspects of a transition to restorative agriculture, participatory action research helps identify and respond to the socioeconomic factors affecting the adoption of new technologies. Santa Rosa farmers identified high start-up costs, a lack of affordable credit, and aversion to risk as major concerns. Though we had good evidence that SPSnu-RF would directly benefit the farmers, these uncertain benefits are insufficient to convince most farmers to shoulder the expense and risks of conversion. We use agroecological principles to increase the provision of ecosystem services to farmers and society, and ecological economics to assess various mechanisms by which

the beneficiaries of those services could contribute to their provision, pragmatically settling on PES as the most political feasible policy for attaining support for farmer adoption. We are working to develop a PES scheme that complements Brazil's New Forest Code, leading to both just and sustainable outcomes.

While we have amassed considerable evidence that our SPSnu-RF systems can help rehabilitate agroecosystems before they collapse while improving farmer livelihoods, we ultimately believe that science, economics and politics are inadequate for the scale of the challenge. Agriculture and other human activities now threaten the capacity of the ecosphere to provide vital ecosystem services essential to all complex life. We cannot rely on economic institutions designed for selfish individuals to solve problems requiring collective action or rely on institutions focused solely on the welfare of humans. We believe a truly restorative economy must be based on the understanding that humanity is part of the planetary biome that sustains all species. While our cells evolved biologically to prioritize the welfare of our bodies over their individual fitness, it will take intentional cultural evolution to develop economic institutions that prioritize the welfare of global ecosystems over that of any individual species. This is not a new idea. Innumerable cultures evolved moral values and economic institutions that allowed them to thrive for millennia. All species must adapt to environmental changes or go extinct, and those that can draw on the greatest genetic diversity are likely to have the greatest success. To evolve a restorative economy, scientists must draw on humanity's immense cultural diversity to adapt, including not only the full gamut of academic disciplines but also different knowledges and values of myriad stakeholders.

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