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Generating regenerative agriculture

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Despite its being still a somewhat vague concept, regenerative agriculture has progressively been gaining momentum and popularity in recent years. While discussing the meaning of the term regenerative agriculture, we propose to link regenerative agriculture with the safe and just Earth system boundaries framework, as the basis for the generation of a paradigm that could robustly ground an appealing regenerative narrative that could nourish the vocation of a new generation of farmers and agronomists. The evaluation of the safe and just Earth system boundaries accounts for Earth system resilience and human well-being in an integrated framework, which is precisely what sustainable agriculture is all about. Our proposal connects the small (the farm) with the colossal (the Earth) in an attempt to confront one of the main sources of criticism for agriculture, i.e., its global environmental impact. The idea is to define the performance of regenerative agriculture in terms of its positive influence on the eight safe and just Earth system boundaries through its sustainable contribution to a highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, and ethically-committed agriculture. Finally, we propose a definition of regenerative agriculture that incorporates the abovementioned proposal.

KEYWORDS

agroecology, biodiversity, earth-system boundaries, resilience, soil health, sustainable agriculture

1 Introduction

The concept of regenerative agriculture (RA) has gained popularity in recent years, with increasing exposure in general and academic media (Bless et al., 2023). Even though it is still a somewhat vague concept, it has almost acritically been accepted by many. As pointed out by Tittonell et al. (2022), part of the popularity of RA is due to its attractive name ("regenerative") as it conveys a positive narrative. Its character as an awakening and promising narrative of a better agricultural future is probably one of the main reasons for the attractiveness of RA, even though it has not yet been clearly defined and, disapprovingly, there are many voices with reservations about it, owing to suspicions of its being a mere marketing campaign of greenwashing and spurious interests. In addition to the choice of the inspiring word "regenerative," another possible reason for the success of RA is that it was initially presented as a "beyond sustainability" approach which would contribute to improve both the environment and the economic viability of agricultural farms (Ikerd, 2021).

But the regenerative narrative is anything but new. In the early 1980s, Rodale (1983) visualized a new agriculture "entirely beyond the current system" that would shift the battle between agriculture and nature towards cooperation, thus reviving the roots of the organic movement. Rodale envisioned RA beyond the concept of sustainability and accentuated the criticality of improving soils and ecosystems, always with an organic vision, without the use of pesticides. Interestingly enough, nowadays, one of the most controversial issues of RA is the

use of herbicides, which practitioners applied for weed control under RA no-tillage systems.

Since the 1980s, The Rodale Institute has been promoting *regenerative organic farming* practices and developing a certification system (Ikerd, 2021). For this certification system, The Rodale Institute proposed three pillars: (i) *soil health*: use of practices such as cover crops, rotations, and conservation tillage; promotion of biodiversity and organic matter (OM) content; no synthetic inputs; (ii) *animal welfare:* the five freedoms (freedom from hunger and thirst; freedom from discomfort; freedom from pain, injury, and disease; freedom to express normal and natural behavior; freedom from fear and distress); grass-fed and pasture-raised livestock; no concentrated feeding operations; no extensive transport; suitable shelter; and (iii) *social fairness:* fair payments and living wages for farmers and farmworkers; safe working conditions; capacity building and freedom of association. In 2015, the Rodale Institute declared that the adoption, on a global scale, of organic management practices could sequester more carbon in soils than it is emitted which, not surprisingly, increased public interest (Hermani, 2020).

The importance of narratives, such as the "regenerative narrative," should never be underestimated. Narratives and stories are fundamental creators of thought and beliefs. In fact, narratives are catalysts of personal, social, and cultural transformations (some good, some bad) as they are effective agents for sense-making and complexity-reduction in this complex world (Kawai et al., 2023). Discourses shape the way we humans conceptualize reality by means of making up a "collective mindscape" that interacts with the material world; in particular, shifting mindscapes is possibly a fundamental intervention towards sustainability (Gordon et al., 2022). There is a fundamental connection between narratives and paradigms (i.e., conceptual patterns of thought, principles, and ideology, generated through the appreciations of their apprehended epistemic truths by certain groups), with the latter enabling meaningful narratives to develop fruitfully (Fink and Yolles, 2012), so to speak, paradigm-based fertile narratives.

According to Thomas Kuhn, well-known for the notions of paradigm shifts and Gestalt switch in science, paradigms are "sets of concepts and practices that define a scientific discipline at any particular period of time" or, as defined in his influential book *The Structure of Scientific Revolutions* (Kuhn, 1962), "universally recognized scientific achievements that, for a time, provide model problems and solutions to a community of researchers." In disagreement with Karl Popper (for an interesting discussion on the Kuhn vs. Popper debate, see Fuller, 2003), for Kuhn, paradigms are essential for scientific progress ("no natural history can be interpreted in the absence of at least some implicit body of intertwined theoretical and methodological belief that permits selection, evaluation, and criticism"). When talking informally about the need for a new paradigm, in most cases, we mean "disciplinary matrix," *sensu* Kuhn, not the meaning of paradigm that commonly appears in dictionaries, i.e., an exemplar, a prototypical example. Importantly, there is a biunivocal relationship between a paradigm and the community adhering to it.

Given the need to find an agricultural model that is both highly-productive and environmentally-friendly, an assortment of agricultural "paradigms" (models, systems) have been proposed in the last decades (see below). Among them, *agroecology* is one of the most comprehensive agricultural paradigms, since it includes social and ecological principles, as well as a variety of biophysical dimensions of agriculture (Tittonell et al., 2022). This fact is manifested in the 10 elements that define agroecology, and which are the backbone of the Tool for Agroecological Performance Evaluation indicator framework (FAO, 2019; Mottet et al., 2021): diversity; co-creation and sharing of knowledge; synergies; efficiency; recycling; resilience; human and social values; culture and food traditions; responsible governance; and circular and solidarity economy. The manifestations of agroecology as a science, a set of practices, and a social movement signify its integrative nature, as revealed by the 13 agroecological principles, which are both aligned and complementary to the abovementioned 10 elements: recycling; input reduction; soil health; animal health; biodiversity; synergy; economic diversification; co-creation of knowledge; social values and diets; fairness; connectivity; land and natural resource governance; and participation (Wezel et al., 2020). Agroecology has much in common with the RA narrative, e.g., focus on soil and ecosystem restoration, promotion of biological interactions and ecosystem services, integration of crops and livestock, and combination of annual and perennial plants (Barrios et al., 2020; Luján Soto et al., 2020; Schreefel et al., 2020; Giller et al., 2021). According to Tittonell et al. (2022), agroecology appears more comprehensive and places more emphasis on the social dimension of sustainability in the definition of the social-ecological system, which might, at least partly, explain why agroecology is more associated with peasant movements (Rosset and Altieri, 2017) whereas RA is increasingly being adopted by large-scale farmers or investors less concerned about issues such as nature conservation or food sovereignty (Tittonell et al., 2022).

But, despite the existence of numerous "sustainable" agricultural models, some of them perhaps as comprehensive and sound as agroecology, the sad truth is that, nowadays, there is broad consensus that the global food system is causing severe environmental and planet degradation (critically, climate change) and loss of biodiversity, while not delivering good nutrition for all (Wezel et al., 2020). In the contemporary, somewhat gloomy, scenario of human population growth and biosphere degradation, could RA be not only an appealing narrative but also a paradigm shift that theoretically and practically drives the long and much-awaited transition towards a categorically highly-productive and environmentally-friendly agriculture? What would RA need to propose to thrust such paradigm shift? To address these questions, it is useful to start with the definition and concept of RA.

The ultimate goal of this article is to trigger discussions, opinions, and thought-provoking debates on the controversial topic of RA and, relevantly, to contribute to those discussions by proposing to link RA with the safe and just Earth system boundaries framework, thus incorporating a planetary, global perspective to RA debates. In the current situation of degradation of our planet (see planetary boundaries below), a truly RA should not only minimize its environmental impact but also contribute to regenerating ecosystems and biodiversity, thereby compensating for the previous damage caused by agricultural production to the integrity of the biosphere. Disturbingly, we are transgressing the planetary boundaries with potential dire consequences to global functions and cycles of the Earth's life-supporting systems, resulting in the alteration of ecological and physicochemical equilibria to a degree beyond their natural resilience (Arguello Velazquez and Negrutiu, 2019). Agriculture is one of the largest contributors to the crossing of planetary boundaries

(Arguello Velazquez and Negrutiu, 2019). Nonetheless, if well-managed, agriculture can enhance the resilience of landscapes to adapt to climate change and other environmental disturbances, while supporting food production and other vital ecosystem services, and improving human health and wellbeing (Felipe-Lucia et al., 2020; Fusco et al., 2023). Sustainable management of agricultural systems can reduce the local and global environmental footprint of agricultural production (Doswald et al., 2014). A truly RA which promotes soil health, conservation of biodiversity, reduction or elimination of contaminating and ecotoxic compounds (i.e., fertilizers, pesticides), rational use of water, reduction of energy consumption and greenhouse gas emissions, etc. will undoubtedly contribute to the recovery of our planet while bringing resilience and sustainability to food production and human wellbeing.

2 Definition and concept of regenerative agriculture

There are so many different definitions and conceptualizations of RA, with examples of both divergence and convergence among them (Schreefel et al., 2020), that one easily becomes frustrated. Many have taken the RA narrative *cum grano salis*, due to reservations regarding its possible lack of axiomatic foundations. There is a great deal of confusion derived from the juxtaposition and amalgamation of principles, practices, processes, outcomes, strategies, and so on, often combined with high-flown rhetoric. Sometimes, a degree of confusion, mingled with grandiloquent rhetoric full of promises, can have an attracting effect because, as expressed in one of his famous aphorisms or "scholia" by the philosopher Nicolás Gómez Dávila, "confused ideas and murky ponds seem deep." The truth is that descriptions of RA often present a heteroclite conglomeration of ontologically diverse categories that leads to confusion and skepticism.

In an attempt to address the lack of a clear definition of RA, Schreefel et al. (2020) evaluated 28 peer-reviewed articles and proposed the following definition: "an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production." Simplifying, the basic idea underlying this definition is "soil conservation for agricultural sustainability and ecosystem services." Likewise, Newton et al. (2020) observed that the numerous definitions of RA were based on processes (i.e., agricultural practices such as minimum tillage, use of cover crops, incorporation of livestock, etc.) and/or expected outcomes (e.g., soil health improvement, carbon sequestration, biodiversity conservation). It is worth mentioning that, while there are differences between them, the concepts of soil conservation and soil health are closely related: *soil conservation* aims to protect the soil as a resource, preventing soil degradation and particularly soil erosion (Panagos et al., 2016), whereas *soil health* is focused on preserving the overall functionality of the soil as a living system (Lehmann et al., 2020).

Terra Genesis International defined RA according to four postulates: (i) it is a system of principles and practices that enhances biodiversity, enriches soils, and improves watersheds and ecosystem services; (ii) it seeks to capture carbon in soil and aboveground biomass; (iii) it offers better yields, climate resilience, and improved health and vitality for farming communities; and (iv) it draws from years of research by communities of agroecology, organic farming, holistic management, and agroforestry. For instance, holistic management, which promotes the beneficial role that livestock can play in agroecosystems, influenced RA regarding the integration of plants and animals (Tittonell et al., 2022).

In an attempt to straighten up the confusion surrounding the concept of RA, Tittonell et al. (2022) distinguished three types of RA: (i) *philosophy RA*, philosophical principles of the type "healing the Earth," "farming in harmony with Nature," etc.; (ii) *development RA*, approaches focused on the restoration of soil and land in smallholder farm contexts and in marginal-degraded environments, as part of larger rural development initiatives; and (iii) *corporate RA*, approaches of large enterprises, from local to multinational, that place emphasis on agricultural practices and frequently present RA as part of their corporate sustainability agendas. These authors warned that presenting RA as synonym of corporate sustainability by large companies might not be positive in terms of getting closer to achieving agricultural sustainability; quite the reverse, it may backfire when either the assured outcomes are not reached or when the association between RA and greenwashing campaigns adversely influences choices by farmers, consumers, governments, etc.

In the current climate change scenario, apart from practices aimed to minimize disturbances and inputs on agroecosystems (e.g., minimum tillage, lower use of pesticides and fertilizers, presence of cover crops, elimination of bare soil and fallow events, increased diversity, incorporation of multispecies cover crops in rotations, use of rotational grazing and animal manure, etc.) (Kenne and Kloot, 2019), RA is also purported to enhance soil carbon sequestration (Hermans et al., 2023), thanks to its focus on building soil OM. Actually, Hermani (2020) considers pivotal the nexus of soil healthy, carbon sequestration, and climate change for the success of RA. Increasing OM content can have other benefits in terms of, for instance, soil structure, porosity, water holding capacity, fertility, and microbial biomass and activity (and microbes can help control soilborne pathogens) (Núñez-Zofío et al., 2011; Epelde et al., 2018; Gómez-Sagasti et al., 2018). Given the severity of the climate crisis, with more frequent extreme climate events and significant changes of extreme temperature in most regions of the world (Shen et al., 2017), an immanent property of any agriculture, like that of many other productive activities, must be to contribute to its mitigation and, consubstantially, to make its utmost to adapt, as best as possible, to their adverse impacts. Climate change intensifies uncertainty and risks for agriculture, thereby increasing the vulnerability of rural populations (Borras et al., 2022). Agrarian responses and struggles to climate change range from migration to locally-based practices to more institutionalized mitigation and adaptation schemes (Borras et al., 2022).

Although no universal definition of RA seems to exist, there does appear to be some acknowledged common principles that could define it in practice: minimize soil disturbance, keep cover on the soil surface, maintain living roots in the soil, foster aboveground and belowground biodiversity (plants, insects, soil biota), integrate animals, etc. (Miller-Klugesherz and Sanderson, 2023). In most documents on RA, the soil plays a key role. So to speak, RA appears to be strongly edapho-centric. This is one of the strongest positive points of RA, as soil health is one of the most important (paradoxically, often forgotten) aspects for the health and sustainability of

agroecosystems. Inexplicably, some still insist on seeing the soil as an inert matrix composed of sand, silt, and clay, despite the fact that, for decades now, scientists have emphasized the importance of its biotic fraction, which is so closely linked to the abiotic fraction that it is often very difficult to unambiguously differentiate them. The importance of the soil's biological component is so large, especially that of the microbial fraction, that Neal et al. (2020) proposed that soil behaves as an extended composite phenotype of the resident microbiome, thus supporting the theory that soil-microbe systems are self-organizing states. For decades, scientists have been aware of the biotic nature of many soil forming processes, and discussed the notion that soils are biotic constructs (van Breemen, 1993). Jacks (1965) defined, somewhat teleologically, soil formation as "the process whereby organisms, using energy absorbed in photosynthesis, make and maintain a habitat."

The soil is a complex ecosystem that harbours an enormous biodiversity responsible for the processes that underpin its functioning. It is not a static matrix; on the contrary, it is processual and dynamic, showing an ontological interdependence between activity and existence. We will never understand it with a reductionist approach, with monadic analyses of isolated elements. Epistemologically speaking, we must approach the edaphic reality as a swarm of interconnections, interactions, and interdependencies among its abiotic and biotic components and properties. Given its dynamic nature, soil has a diachronic identity dependent on natural and human-induced disturbances, including, of course, agricultural practices. We must embrace the complexity of the soil ecosystem, largely derived from its heterogeneity, and accept the associated uncertainty. Among other corollaries, this complexity is responsible for the fact that the short-term effects of a particular practice or agricultural system are often different from the medium- and long-term effects (sometimes they are not only different but contradictory), which implies the need for a deeper understanding of the temporary and temporal dynamics in the evolution of soil properties and its health.

As pointed out by LaCanne and Lundgren (2018), RA aims to profitably merge farming with natural resource conservation, paying special attention to soil health and biodiversity. It is important to emphasize that the anthropocentric perspective (farming) should not be pitted against the biocentric or ecocentric perspective (natural conservation) because the survival of both is strongly dependent on their harmonious coexistence (same for the "economy vs. ecology" debate). Regenerative agriculture can be understood as a hybrid standpoint that seeks to reconcile the deep-rooted tensions in the longstanding debate between productivism and post-productivism, by maximizing crop yields and ensuring economic profitability while benefiting the environment (Beacham et al., 2023).

But for farmers and agronomists to embrace the RA paradigm, provided it already deserves such term, it is essential that we all understand and accept, sidestepping infertile ideological diatribes and accusations, that today's agriculture needs to address a process of "philosophical regeneration," because it is an indisputable fact that, hitherto, many gains in agricultural production and productivity have been achieved at the expense of the exploitation and senseless destruction of the Earth's wildlife, biodiversity, and natural resources. Actually, despite decades of promising alternative agriculture discourses and models, paradoxically, the truth is that, in most countries, the industrial agricultural model still dominates by a wide margin in terms of both occupied land and economic relevance. Despite many concepts, proposals, initiatives, and calls for agriculture to become more environmentally-sustainable (e.g., RA, ecological agriculture, organic farming, conservation agriculture, agroecology, permaculture, agroforestry, biodynamic farming, holistic management, etc.), the reality is that the agricultural sector is still dominated by an imbalanced narrative that heavily privileges production over conservation (Hunter et al., 2017). In spite of many efforts, we still fail to align and balance the three pillars of sustainability, in part, because of the difficulty in articulating such reconciliation, to some extent, due to the presence of "uncomfortable" trade-offs. The very notion of sustainability is still characterized by context-specificity and ontological openness, meaning that any rigorous operationalization requires explicit description of how it is understood (Purvis et al., 2019).

The sustainability debate is inextricably linked to the field of ethics. On the issue at hand, agricultural ethics includes different moral issues, such as the interference with the course of nature, animal welfare, and the effects of agricultural practices and customs on social conditions (Comstock, 2000). More and more, our society demands that food production must take into consideration social values, environmental protection, animal welfare, and public health. An ethical agriculture must be respectful of environmental, animal, and human health (see One Health below). Agriculture is a human activity with high externalities (Turk and Ivancic, 2011), as well as the major and most extensive human-environment interaction, then, it is only common-sense that we earnestly consider its ethical dimensions (Zimdahl, 2000; Malekhoseini et al., 2019). The field of agricultural ethics often analyses the challenges and crises of the agricultural sector to achieve sustainability; actually, for some, agricultural ethics is a redefinition of agricultural sustainability (Malekhoseini et al., 2019). From an ethical point of view, apart from an environmental and economic analysis, a proper axiological assessment of agricultural systems should also capture other key issues such as intergenerational and intragenerational equality, social justice, and conditions of labour. It is worth remembering the Kantian categorical imperative: "Act only according to that maxim whereby you can at the same time will that it should become a universal law."

But the vital need to orchestrate agricultural production with nature conservation (economics with ecology), as promoted by the RA standpoint, is not a new proposal. As an example, the advocates of conservation agriculture have long been promoting minimum soil disturbance, permanent soil cover, and crop rotations, as well as emphasizing the criticality of restoring soil health and agroecosystem services (Kumawat et al., 2023). The three pillars of conservation agriculture (minimum soil disturbance using no-tillage or conservation tillage; maintenance of ground cover using crop residue, cover crops, or mulching; and crop diversification through crop rotations and intercropping) (Ahmed et al., 2024) are regularly included in discussions on RA. The cruciality of promoting soil conservation and soil health, biodiversity, ecosystem services (beyond food production), and sustainability in agriculture is not a new issue; in fact, it has been emphasized by many for decades (e.g., advocates of organic farming, agroecology, permaculture, etc.). From a purely agronomical viewpoint, RA is neither a new concept nor a new set of practices that have suddenly arrived to revolutionize the farming arena.

Plausibly inspired by the connotations associated to the word "regeneration" (renewal, rebirth, revival, restoration, recovery), some

advocates of RA are probably mainly driven by a desire to change the *status quo* and become better farmers and citizens who, through their activity, contribute not only to food production and the economic sustainability of their families, but also to a better world. Yet again, this is anything but new. In all sectors, and certainly within the agricultural sector, there have always been people who see beyond the simple, and no doubt respectable, economic profitability of their business, and want to contribute to a better world, thus giving a greater transcendence to their lives.

There is always the possibility that some may use the label RA simply for spurious interests linked to greenwashing. In fact, RA has often been accused of being a buzzword that many use just for greenwashing purposes (Wilson et al., 2024). Without debating the issue, just to mention that greenwashing is not only dishonest and unethical, but quite often also the result of sheer ignorance and failed or neglected personal growth. Yet, beyond RA, in recent years, the utilization of farming systems for the support of political and/or social beliefs and interests is becoming common practice, which often makes it difficult to have debates focused exclusively on scientific knowledge acquired through field and laboratory research. In any case, it must be emphasized that all knowledge is political and, then, never neutral (Rosset and Altieri, 2017; Jansen and Walters, 2022), as it is embedded in a historical and political system of constructed rules. Similarly, technological advancements, intentionally or unintentionally, are not neutral, many times favoring some social groups or socioeconomic interests over others.

One of the initial aims of RA was to make farmers more responsible and committed citizens. This constructive, optimistic, and empowering focus on personal growth and responsibility has possibly played a role in the RA expansion. But the transition to a sustainable food system has a political component that goes beyond individual awareness and good actions and requires collective initiatives. By paying attention to only individual actions at the farm level, RA might even hamper the transition to a sustainable food system, since such transition requires the two levels of sustainability described by Terrier et al. (2013): restricted sustainability (sustainability objectives of the farmer for the farm) and extended sustainability (contribution to the sustainability at the level of territory, region, country or world), the latter allowing the identification of agricultural social objectives.

In summary, for the time being, there is no agreed definition of RA. However, the lack of a definition is not an insurmountable obstacle to developing a field of knowledge. One of the best illustrations of this circumstance is the field of biology that, lacking a definition of life, has been successfully focused for centuries on the study of living beings. An example much closer to the subject matter at hand is the concept of soil health, a topic that, after decades of discussion, is still a matter of much debate (Lehmann et al., 2020; Janzen et al., 2021). Also, sustainable farming does not have a precise definition (Ikerd, 2021). In a nutshell, so to speak, the lack of a definition does not lead inexorably to an epistemological Babel. Besides, when a concept is contested, its disapproval does not necessarily disappear by a better definition, because concepts are often inextricably linked to practice choices, and the practices will remain contested (Struik and Kuyper, 2017). Moreover, definitions and conceptualizations frequently need to show a certain degree of flexibility and an evolving character, in order to cope with the changes, scenarios, novel perspectives or interests to come. In other words, they must have a certain degree of freedom and, recurrently, be more spectral than categorical. The lack of an agreed definition of RA might even be considered a positive aspect, as it could facilitate that different people try different things in their "regenerative journey." By contrast, that lack might facilitate the unethical use of the term RA for greenwashing purposes.

So, is there anything really new within the field of RA? If not, could we make RA a truly novel paradigm that robustly grounds an appealing narrative that will nourish the vocation of a new generation of farmers and agronomists? Could we generate a really RA? Before answering these questions, it is appropriate to first address the following: Do we really need to regenerate agriculture? (Section 3). Can we use relevant contemporary concepts to generate a truly RA? (Section 4).

3 Do we really need to regenerate agriculture?

The demographic, environmental, and planetary situations call for a clear-cut affirmative answer to this question. We cannot continue with "agribusiness as usual." Agriculture must indisputably be transformed because it has greatly contributed to an unsustainable present in which the stability of planet Earth is compromised. Beyond the debate over what percentage increase in agricultural production is needed to feed the growing human population in the coming decades (Hunter et al., 2017; van Dijk et al., 2021), a debate which must always include the food waste issue and the paradoxical coexistence of undernutrition and a global overweight and obesity epidemic (the so-called globesity) (Vasileva et al., 2018), it seems incontestable that a turning point has been reached (see ecological overshoot and planetary boundaries below) and that agriculture will be irrefutably called upon to both feed people AND ensure a healthy environment and planet. Without pretending to be infallible or categorical, it seems highly likely that one of the tenets or apothegms that will mark the future development of agriculture will be: "make sure your agriculture takes care of your planet so that your planet takes care of your agriculture." If we cross the planetary boundaries that define the safe operating space for humanity, planet Earth will not only be less habitable for us humans but will also be a place where agriculture will be much more difficult to prosper.

But the need to address the long-awaited transition to true sustainability is not only an issue for agriculture, it is an issue for all sectors of the economy. For those recalcitrant to transitions and changes, more or less gradual, more or less drastic, it is important to remember that changes are part of all evolving systems, and that novelty generation is a fundamental concept of selection (Wong et al., 2023); in fact, evolution implies change over time (though, of course, not all change is evolution). Transformation involves novelty and innovation (Folke et al., 2010), both of which are required (i) for systems to remain dynamic and functioning; (ii) to keep complex systems resilient; and (iii) to create novel structures and dynamics in the wake of system crashes (Gunderson and Holling, 2002; Allen and Holling, 2010). In an era such as ours, characterized by such rapid changes in both Earth system indicators and global socio-economic indicators that it has been termed the Great Acceleration (Head et al., 2021; Shoshitaishvili, 2021), it would be illusory to think that we can survive with the same mental coordinates, behavioral codes, and standards that have "functioned" so far.

Although a discussion on the technological advances in food production is outside the scope of this article, it is inevitable to take into account that new players have appeared in the food production arena: new sources (insects, seaweed, jellyfish, etc.) and production systems (hydroponics, indoor farming, cell-based production, plant-based meat, 3D printing-based production, etc.) (Tan et al., 2024). Taking into consideration the race between human population growth and food supply (Miladinov, 2023), as well as the need to limit the area of land dedicated to agricultural production in order to protect the integrity of the biosphere, these alternative systems should be seen as complementary to agriculture and not as competitors. In the current scenario of planet degradation, the greatest risk for agriculture is probably not the advent of innovative food production systems (systems not based on the soil resource, with little or no dependence on weather or climate), but the inability to make agriculture a more environmentally-sustainable and climate-neutral activity. If agriculture does not succeed in the necessary convergence between production and conservation, it is conceivable that it will be, partially or almost completely, sooner or later, replaced by these alternative systems.

Agriculture must be approached as a complex, adaptive social-ecological system with a social and an ecological subsystem (Rivera-Ferre et al., 2013). The dynamics of complex social-ecological systems in response to disturbances can be interpreted according to the theory of *adaptive cycles*, one of the heuristics applied to the understanding of the behavior of social-ecological systems (together with resilience, adaptability, transformability, and panarchy) (Holling, 2001; Gunderson and Holling, 2002; Walker et al., 2004, 2006). Adaptive cycles have four phases: growth or exploitation (r); conservation (K); collapse or release (omega); and reorganization (alpha). When the resilience of a social-ecological system is exceeded, the system might be altered or collapse, entering the omega phase characterized by abrupt change and high uncertainty (Gunderson and Holling, 2002). Our food production system is threatened by a number of pressures of diverse nature (demographic, economic, geopolitical, environmental, and climatic) that could conceivably overwhelm the resilience of the global food production system. In such an event, it is plausible that new food production systems could emerge (reorganization phase) and become dominant, such as, for instance, high-tech, indoor, and/or laboratory-based systems.

Historically, revolutions and evolutions in agriculture have, for the most part, been driven by mechanical-machinery developments, genetic improvements, and chemical innovations. Odds-on, in the coming decades, the most radical transformations will be driven by automation developments, artificial intelligence, advanced materials, internet of things, and similar cutting-edge technologies currently at the forefront of scientific and technological advancements. These innovations should not be an end in themselves, but a means to make agriculture more environmentally-sustainable and, simultaneously, to produce healthier and more affordable food options. In relation to the introduction of new technologies in agriculture, it is advisable not to fall into technolatry-technotheism nor into technophobia (after all, there is nothing more human than technology), but to ensure that technology is always human-centered. In the next decades, the three domains of sustainability (the ecological, social, and economic pillars of sustainability) will be radically affected by a fourth domain: the technological domain. But it is most likely that many technological advances will not be accessible for small landowners with limited resources, which represent the majority of farmers worldwide, especially in the Global South (Khumairoh et al., 2012). As a result, for at least some considerable time, the increase in crop yield in many small farms will mostly depend on improved management practices, use of organic resources to enhance soil fertility and structure, a better control of weeds, pests and diseases, and the accessibility of high-quality, climate-resilient, and genetically-diverse crop species. One of the often-overlooked risks of a highly technified agriculture, remotely managed through robots, drones, sensors, advanced machinery, etc. is the emotional disaffection of farmers from the land, with negative consequences for the creation of inspiring narratives.

According to Gremmen (2022), there are two main agricultural scenarios: (i) the first aims to intensify technology-driven research (another green revolution super-charged by high-technology) and involves ways to reduce the impact of agriculture on the environment, biodiversity, and wilderness; and (ii) the second aims to switch to nature-based systems, many of them framed, explicitly or implicitly, as a "(re)turn to Nature," conceivably, in some cases falling into the *argumentum ad naturam* fallacy. Many nature-based agricultural systems are now often referred to as RA, with a focus on soil fertility, minimal tillage, no chemicals, and intercropping (Sumberg, 2022). If truth be told, there are so many similarities, many more than differences, in interests, practices, beliefs, principles, etc. among many of the schools of thought that strive for a sustainable agriculture that, though the idea might be anathema to some (especially, to those dealing with certification systems), one wonders whether it would not be a good idea for them to merge according to the maxim "unity is strength." There are probably too many "sustainable" systems "on offer" (organic farming, agroecology, RA, conservation agriculture, permaculture, precision agriculture, climate-smart agriculture, sustainable intensification, biodynamic farming, holistic management, biomimetic agriculture, etc.) whose advocates compete with each other in terms of recognition and attraction of members to their school of thought and interest. A description of the many similarities and fewer differences among all these systems is not the subject of this article. However, it is worth recalling the old adage "cooperation is better than confrontation." We humans sometimes get entangled in byzantine discussions due to dogmatic stubbornness, ideological asymmetries, cognitive and/or cultural biases, supposed customary "rights," erroneous unquestionable "certainties," and so on, but once the dust settles, one undeniable fact that is always worth remembering (especially if one has an awareness of otherness) emerges: dialogue and collaboration are better than monologue and conflict. It is important to create links (fuse?) among agricultural schools by understanding and demonstrating that many of the different viewpoints and disputes are simply based on spatio-temporal conjunctures and/or partial and changing casuistries. Many of the differences between productivists and conservationists can be reduced to a difference in the temporal perspective of analysis: the former tend to focus more on short-term benefits while the latter on medium- and long-term benefits. Understanding this fact facilitates the deconstruction of fictitious Cartesian dichotomies and dualities that present different entities and categories as ontological planes at odds with each other, when in many cases there is a continuum between two traditionally opposed positions.

In relation to this, during discussions on the "land-sharing vs. land-sparing" debate (Sidemo-Holm et al., 2021), those supporting the dominating agricultural productivity paradigm often argue that

agricultural intensification indirectly meets the environmental goals by making possible land-sparing for wilderness, wildlife, and biodiversity (Daum et al., 2023). But the reality is that land-sparing rarely happens without strict explicit enforcement of specifically related set-aside policies (Daum et al., 2023; Goulart et al., 2023; Grass et al., 2019). Given the state of degradation of our planet, and hence the imperative need to minimize the impact of all economic sectors on the integrity of the biosphere and the Earth system, the land-sharing vs. land-sparing debate makes no sense if by land-sparing we mean that, in the areas dedicated to high-yield farming, one can do whatever one wants on such land without any concern for the ecological impact. We must dedicate land exclusively to nature conservation (see Half-Earth below), while introducing soil health practices, biodiversity, and a philosophical and practical respect for nature into agricultural lands, using all our knowledge, technological capacity, innovation, and creativity, in order to make them highly productive in terms of food production and other ecosystem services. Finally, Folberth et al. (2020) stated that the release of cropland over large regions can entail important socioeconomic implications with respect to livelihoods and affect regional food self-sufficiency. Attaining ambitious land-sparing targets demands a rapid dissemination and integration of agro-technologies across society, to avoid cropland expansion while maintaining livelihoods of populations affected by the change (Folberth et al., 2020). It is crucial to also take labour market issues into serious consideration since, in a land-sparing system, far fewer farmers may be needed with concomitant social consequences.

Returning to the issue of a truly RA that is not simply a repetition of known practices and concepts, we must first be aware of the fact that the environmental scenario in which agriculture is being (and will be) developed has substantially changed in the last decades, and not for the better, and, accordingly, agricultural management must now operate under the maxim "business as usual is not an option." Above all, the climate crisis in progress is affecting most aspects of our lives, as well as the lives of most living organisms on this planet, included, of course, crop plants and livestock (Habib-Ur-Rahman et al., 2022). But it is not only climate change. Nowadays, we are all familiar with the terms loss of biodiversity, deforestation, land degradation, ocean acidification, global pollution, waste generation, resource depletion, and so forth. But one of the problems with climate change is that, given the severity of its consequences, it has largely overshadowed all these other issues, which in turn obscures the fact that they are all interconnected and have a systemic nature.

As manifested by the ecological footprint (an indicator of our demand for biotic resources), since the mid-1970s we are in ecological overshoot, meaning that, since then, humanity has been using more renewable natural resources than our planet can regenerate (McBain et al., 2017). Possibly, the most important principle of sustainability is to live within the regenerative capacity of the biosphere, a principle we are failing to live up to despite its criticality. Our economy (including that linked to the agricultural sector) depends on the planet's natural capital, which provides all ecological services and natural resources (Wackernagel et al., 2002). Consuming the natural capital beyond its regenerative capacity leads to depletion of the capital stock (Wackernagel et al., 2002), with disturbing consequences for our civilization, many of them still probably impossible to predict. Among other corollaries, a continued ecological overshoot implies that humanity is progressively exposed to risks, actually a palette of them, related to the departure from Holocene ranges of Earth system variability, in particular, due to the approach of two planetary boundaries: land-use change and climate change (Rockström et al., 2009a,b; McBain et al., 2017).

There is no doubt that we need to address an ecological transition. But transitions normally take time and are often accompanied by confusion, suffering, and uncertainty, and frequently by a higher or lower dose of chaos. In this and all situations, it is crucial to direct efforts towards building system resilience. However, it must be remembered that resilience, in its four components (latitude, resistance, precariousness, and panarchy) (Walker et al., 2004), is a positive attribute only if the system under consideration is sustainable and well-operating in the first place (many social-ecological systems operate in both resilient and unsustainable ways) (Lyytimäki et al., 2023). But for the evaluation of system resilience to go beyond abstract conceptualizations and reach concrete operationalizations, system signals which track the dynamics of change at explicit and objective scales are required (Sundstrom and Allen, 2019). As the Earth system is approaching or exceeding thresholds that might cause the end of the Holocene stability domain, we must foster systems that contribute to Earth system resilience (Folke et al., 2010), including, of course, agricultural systems, as agriculture is partly responsible for the approaching and crossing of those planetary boundaries.

In summary, the existing state of environmental and planet degradation, together with the loss of biodiversity and wilderness, the ecological overshoot, and the rate of human population growth, make it compulsory to drastically rethink the current agricultural model, i.e., to truly regenerate agriculture. Somewhat paradoxically, given the level of vagueness, confusion, conflict, overexaggeration and overly ambitious claims still associated to the RA concept, it also seems necessary to regenerate RA itself. If not, there is the risk of RA being just another buzz term with inflated expectations that will then be discarded when the overblown expectations have been disillusioned (Hermani, 2020).

4 Can we use relevant contemporary concepts to generate a truly regenerative agriculture?

In the proscenium of the current environmental scenario, the *Planetary Boundaries Framework* (Rockström et al., 2009a,b) is attracting great interest within science, policy, and practice. The planetary boundaries framework came to complement the *sustainability* (Pisiotis and Peschner, 2020) and *ecosystem services* (Millennium Ecosystem Assessment, 2005) paradigms that have been centre stage since their inception. The planetary boundaries framework demarcates a "safe operating space for humanity" according to nine processes that regulate the stability of the Earth system: climate change, introduction of novel entities, biogeochemical flows, land-system change, freshwater use, atmospheric aerosol loading, ocean acidification, stratospheric ozone depletion, and change in biosphere integrity (Steffen et al., 2015). At the present time, six of the nine boundaries have been crossed (Steffen et al., 2015; Persson et al., 2022; Wang-Erlandsson et al., 2022), revealing the level of degradation of our planet (Ripple et al., 2017, 2022), to a great extent, owing to the ecological overshoot. Relevantly, soil degradation

has been proposed as the 10th Earth-system process for the planetary boundaries framework (Kraamwinkel et al., 2021).

Rockström et al. (2024) proposed the *Planetary Commons Framework* which, unlike the global commons framework, incorporates not only globally shared geographic regions but also the biophysical systems that regulate the resilience and state, and hence livability, of planet Earth. This framework demands a change from a focus only on governing shared resources beyond national jurisdiction to one that secures critical Earth-system functions irrespective of national boundaries.

Different proposals are being put forward to achieve the 17 *Sustainable Development Goals*-SDGs within the planetary boundaries, owing, in part, to the possibility of conflict between the three environmental SDGs (SDGs 13, 14, and 15) and the 14 socio-economic SDGs (Randers et al., 2018, 2019). Not surprisingly, one of the proposed actions was to accelerate productivity in sustainable food chains (Randers et al., 2018).

Alkorta and Garbisu (2024) proposed to expand the *One Health* concept (Pitt and Gunn, 2024) to include not only human, animal, and environmental health, but also the Earth-system processes of the planetary boundaries framework. To this purpose, the authors pointed out the connections between all the processes included in the planetary boundaries framework and the One Health quintessential issue, i.e., antibiotic resistance. Montgomery et al. (2024) argued that a greater understanding of soil health and its many links to agricultural practices could prove foundational to many of the challenges that both the One Health and Planetary Health initiatives aim to address. These authors also outlined the many benefits of RA for soil health and, hence, for One Health and Planetary Health.

While the One Health approach aspires to balance and optimize the health of people, animals, and ecosystems (recognizing that the health of humans, animals, and the environment are interdependent), the *Planetary Health* concept (Correia et al., 2021) aims to expand the One Health concept to include ecosystem- and biosphere-level effects, as well as to consider planetary biogeochemical boundaries. Thus, the Rockefeller Foundation defined planetary health as "the health of human civilizations and the natural systems on which they depend" (Whitmee et al., 2015).

Many other analogous concepts, partly or wholly, directly or indirectly, focused on the links between human health and the health of the environment, ecosystems and, in general, planet Earth have emerged in recent years (EcoHealth, Global Health, Environmental Health, etc.) (Lerner and Berg, 2017; Harrison et al., 2019), creating a certain amount of confusion derived from the occurrence of polysemy, lexical ambiguity, semantic overlapping, and an excessive degree of nuance, resulting in the construction of deceptive conceptual barriers and boundaries, as well as the generation of false scientific silos, that subvert the understanding and acknowledgement of the close connectedness, interrelationship, and interdependency among them. Instead of building non-existent walls between some of these concepts, we must build conceptual bridges, based on the connections between them, because the interweaving of epistemologically diverse frameworks and paradigms about a given subject often result in a deeper understanding and better solutions.

The *Doughnut Economics Framework* (Raworth, 2017), another attempt to shift modern-day social-ecological systems towards sustainability, highlights the need for an environmentally-safe and socially-just space for humanity, according to the notion of "meeting people's needs without disrupting the biophysical processes that regulate the stability of the Earth system" (Turner and Wills, 2022). In the same line of thought, Rockström et al. (2023) proposed eight *Safe and Just Earth System Boundaries* "for sustaining the global commons that regulate the state of the planet, protect other species, generate nature's contributions to people, reduce significant harm to humans, and support inclusive human development." These boundaries were established for eight domains (climate-temperature, biosphere-natural ecosystem area, biosphere-functional integrity, water-surface water flows, water-groundwater levels, nutrient cycles-nitrogen, nutrient cycles-phosphorus, and atmosphere-aerosol loading), covering climate, the biosphere, freshwater, nutrients, and air pollution (Rockström et al., 2023). As in the case of the planetary boundaries, this framework also covered the issue of the novel entities ("new substances, new forms of existing substances, and modified life forms that could have large-scale unwanted geophysical or biological impacts on the Earth system") and other pollutants, such as microplastics, PFAS (per- and polyfluorinated alkyl substances), antibiotics, radioactive waste, and heavy metals.

The Earth's biodiversity in all its components (genes, species, and ecosystems) is disappearing at a disturbing rate. In order to combat the Eremocene (*sensu* E. O. Wilson) (Pimm, 2022) and to halt the "sixth mass extinction" of biological species in the Anthropocene, many initiatives have been proposed. The *Half-Earth* proposal (Locke, 2013; Wilson, 2016; Dinerstein et al., 2017) is progressively having an influence on global environmental governance, as reflected by the calls to increase the global protected area target of the Convention on Biological Diversity from 17% of Earth's land by 2020 to 30% by 2030, and 50% by 2050 (Convention on Biological Diversity, 2018; Ellis, 2019). Among the challenges associated with this initiative (Ellis, 2019; Ellis and Mehrabi, 2019), it must be accentuated that this large-scale land demand for conservation will compete with land demand for agriculture (Mehrabi et al., 2018). But, while it is true that agriculture has contributed to the degradation of the planet and, in particular, to the loss of biodiversity (Steffen et al., 2015), it is equally true that agriculture can contribute to its recovery and regeneration. We need an agricultural development that successfully integrates global needs and constraints with local agricultural practices and possibilities. For better or worse, what is done in the local agricultural sphere can have global environmental, social, and economic implications. In fact, given the magnitude of the world's agricultural activity (a large part of the Earth's surface is dedicated to agriculture), its global environmental consequences are the main source of its criticism, some of them possibly opinionated but others worth of consideration.

Biodiversity is not only key to the functioning of the biosphere but also to agroecosystem resilience. Regrettably, more and more people are nowadays disconnected from natural ecosystems and are not aware of the many benefits and services we obtain from them. Actually, during their identification of the *Anthropocene Evolutionary Traps* ("phenomena manifesting at the global scale of human society, causing one or more human practices to become maladaptive"), Jørgensen et al. (2023) included "biosphere disconnect," with biosphere illiteracy as indicator, as an evolutionary trap.

In relation to ecosystem services, an issue incorporated into many discussions on RA, the notion of *Nature's Contributions to People*-NCP recognizes the key and pervasive prominence that culture plays in defining the links between people and nature, and elevates the role of

local knowledge in understanding NCP (Díaz et al., 2018). The focus of the NCP concept on the importance of culture and local knowledge (Díaz et al., 2018) makes it particularly suitable for the field of agriculture, in which culture and local knowledge are cornerstones of its activity and core body of knowledge. Given the importance of cultural values, traditions, and perceptions in the agricultural sphere, any proposal for a new agricultural worldview should take social-cultural aspects into deep consideration (and not attempt to impose a specific, highly-detailed set of universally-applicable norms) and present an integrative philosophical framework that accommodates different worldviews and allows space for diverse cultural values and beliefs. When contemplating a new agricultural paradigm, it is advisable to define a theoretical-epistemological framework (as philosophical foundation of the new perspective) that could be deployed in a broad casuistry of different contexts, scales, and socio-economic and cultural backgrounds.

Finally, the *Biomimicry* field (defined by the Biomimicry Institute as "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies") aims to reconnect humans with nature to regenerate degraded ecosystems (Ilieva et al., 2022). Biomimicry takes nature as a model to meet the challenges of sustainable development (ISO 18458, 2015). Then, not surprisingly, RA has been proposed as a biomimetic technology (Gremmen, 2022). The interpretation of RA as a biomimetic technology was proposed in an attempt to solve the conceptual limitations of RA. Biomimetic agriculture (e.g., biomimetic RA), and in particular biomimetic agricultural designs, not only compels us to imitate natural forms and processes, but reminds us that agriculture must be embedded in- and participate in ecosystems (Gremmen, 2022).

From all of the above, it can be concluded that there are many concepts, paradigms, frameworks, etc. that can be used to inspire, especially from a theoretical-philosophical perspective, the generation of a truly RA.

5 Towards a paradigm-based fertile regenerative narrative

From the above information, five points on which there seems to be a consensus can be extracted: (i) there is no agreed definition of RA; for many, it is a vague concept, or much worse, a buzzword used for greenwashing purposes; (ii) agriculture has contributed to the degradation of our planet and the crossing of the planetary boundaries; (iii) owing to the state of degradation of planet Earth, caused by an unsustainable development model that has resulted in ecological overshoot and a climate crisis, a growing number of scientists, and the society in general, are calling for a much more environmentally-sustainable agriculture; (iv) the agricultural field has close links with many of the aforementioned concepts and paradigms that deal with our interaction with the environment, the biosphere, and the planet (One Health, Planetary Health, Planetary Boundaries, Safe and Just Earth System Boundaries, Planetary Commons, Sustainable Development Goals, Biomimicry, Ecological Overshoot, Doughnut Economics, etc.); and (v) there is an urgent need to regenerate agriculture so that "it takes care of the planet for the planet to take care of agriculture." In the light of the emergence of innovative food production systems not based on the soil resource, for agriculture to prosper, it must become a more environmentally-sustainable and climate-neutral activity.

In the light of the above, and in an attempt to make RA a truly novel paradigm that could support a fertile regenerative narrative, we propose to define the performance of RA in terms of its positive influence on the eight safe and just Earth system boundaries through its sustainable contribution to a highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, and ethically-committed agriculture (Figure 1). In this regard, we propose the following tentative definition of RA: "an approach to sustainable farming that uses soil health, biodiversity, and climate-resilient genetically-diverse crops as the basis of a highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, and ethically-committed agriculture that positively contributes to the provisioning of multiple ecosystem services and, in particular, to the safe and just Earth system boundaries."

Before proceeding any further, it must be emphasized that the generation of definitions, concepts, paradigms, and so on is a boundless and never-ending process, because they must always be developed further as more data, information, knowledge, interests, perspectives, etc. are available or become important. Definitions, concepts, archetypes, etc. change and evolve over time, and are often contextual, meaning that what looks good today might not look so good tomorrow. But, most importantly, as stated by Sojka and Upchurch (1999), we must remember that "our children and grandchildren… will not care whether we crafted our definitions or diagnostics well. They will care if they are well fed, whether there are still woods to walk in and streams to splash in—in short, whether or not we helped solve their problems…."

In the narrative that RA can sow and cultivate, the destination cannot only be the generation of food with as low an ecological footprint as possible, but also, simultaneously, the generation of habitats, biodiversity, biotic interactions, trophic networks, resilience, and the like, as well as the positive contribution to the Earth system functioning and, in particular, to the safe and just Earth system boundaries. Among all the concepts described above, why choose the safe and just Earth system boundaries to provide a conceptual framework for RA? Firstly, because the assessment performed to define these boundaries was built upon the planetary boundaries framework, the doughnut economics framework, and the SDGs (Rockström et al., 2023), three of the most recognized relevant frameworks. In turn, an expanded One Health concept was proposed to include also the planetary boundaries (Alkorta and Garbisu, 2024), which are closely related to the safe and just Earth system boundaries. Besides, soil health, a fundamental attribute of RA, has been reported to be a master variable for regulating critical Earth-system processes (Kopittke et al., 2021). Soil degradation has been argued to constitute a key Earth system process that should be added to the planetary boundaries (Kraamwinkel et al., 2021). Given the criticality of soil conservation and soil health for RA, these linkages support the here proposed connection between the safe and just Earth system boundaries and RA. Yet, it must be remembered that agriculture not only depends on a fertile and healthy soil, but also on the existence of high-quality, climate-resilient crops with a high level of genetic diversity within each variety (same for livestock). Moreover, the assessment of the safe and just Earth system boundaries accounts for both Earth system resilience and human well-being in an integrated framework, which is exactly what sustainable agriculture is all about.

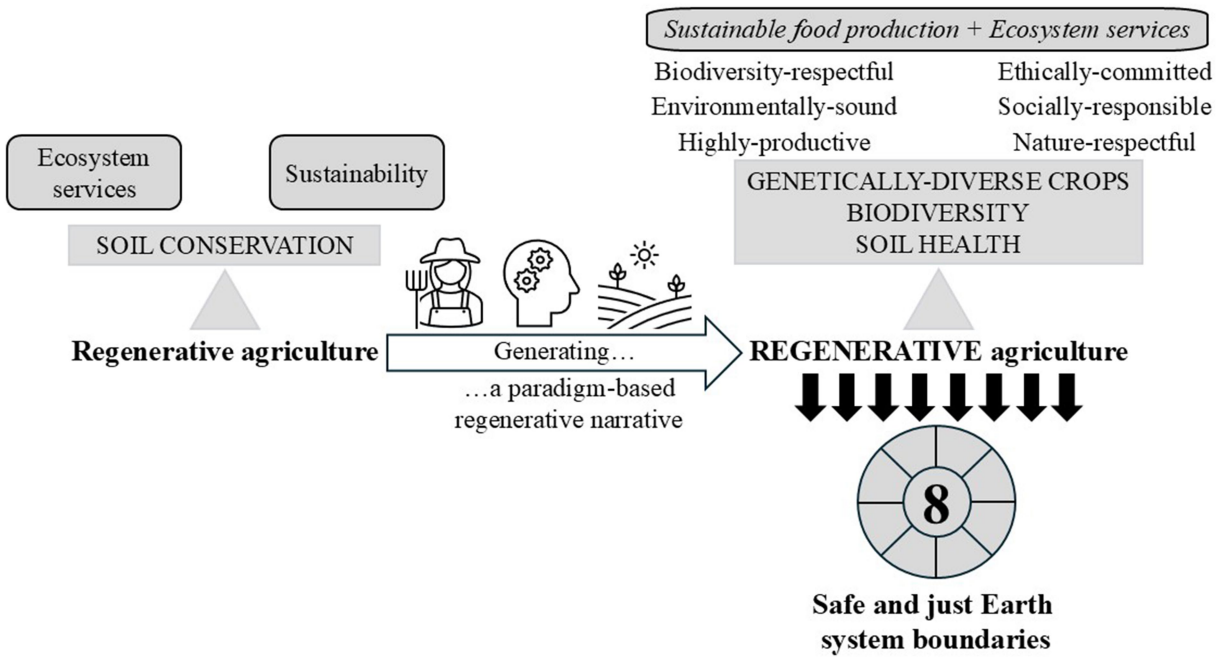

FIGURE 1
Schematic representation of the proposal to link regenerative agriculture with the safe and just Earth system boundaries framework.

Also, the agricultural activity is related to each and every one of the eight domains selected to establish the safe and just Earth system boundaries. Furthermore, its global environmental impact is possibly the main source of criticism for agriculture, and the safe and just Earth system boundaries are focused on the Earth system, being thus perfectly suited for global assessments and perspectives. Finally, the safe and just Earth system boundaries incorporate ethically-significant justice criteria, such as intergenerational justice, and intragenerational justice between countries, communities, and individuals via an intersectional lens. In consequence, by linking agricultural activity with the safe and just Earth system boundaries, all the attributes that a truly regenerative agriculture should have (i.e., highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, ethically-committed) are covered.

Apart from the promotion of soil health, biodiversity, and climate-resilient genetically-diverse crops, RA should be characterized by the use of practices that positively contribute to the safe and just Earth system boundaries. For example, our proposal implies that RA must encourage the use of practices that (i) mitigate climate change through soil carbon sequestration and/or reduction in the emissions of greenhouse gases from soil (climate domain); (ii) reduce energy consumption (e.g., through proper selection, maintenance, and use of machinery) to minimize the carbon footprint (climate domain); (iii) respect the integrity of ecosystems, including the soil ecosystem (biosphere domain); (iv) protect and promote aboveground and belowground biodiversity, including plants, animals, fungi, protists, bacteria, and archaea (biosphere domain); (v) make a rational use of the water resource (water domain); (vi) minimize the use of fertilizers (nutrient cycles domain); (vii) reduce ammonia emissions through a better management of livestock, manure handling and storage, and of the application of manure or slurry to soils (aerosols domain); (viii) reduce soil erosion (aerosols domain); (ix) reduce or eliminate the use of pesticides (novel entities); and (x) control the entry of metals, antibiotics, PFAS, and microplastics via, for instance, the application of amendments, such as biosolids, sewage sludge, or manure (novel entities). This is not an exhaustive list but only a compendium of examples of how agricultural practices can be linked to the safe and just Earth system boundaries.

Many of the practices that bring these benefits coincide with those that have been recommended for years by the advocates of sustainable agriculture, since they are practices that, through decades of experience, have shown their potential positive effects on agroecosystems: (i) no or minimum tillage; (ii) maximum possible reduction in the use of pesticides and fertilizers; (iii) use of multispecies cover crops; (iv) elimination of bare soil and fallow events; (v) incorporation of livestock; (vi) rotational grazing; (vii) organic fertilization with high quality amendments; (viii) increased plant diversity; (ix) establishment of flowering fields; (x) creation of edge habitats; (xi) combination of annuals and perennials; etc. In this sense, it is not necessary to have an epiphany to understand what RA is all about, but simply to internalize and apply a series of practices that have already demonstrated their potential benefits for soil health, biodiversity, and all the ecosystem services that agroecosystems can provide. But, given the complexity of socio-ecological farming systems and, specifically, the complexity and heterogeneity of the soil, the suitability of these practices will depend on casuistry (e.g., crop varieties, resources) and the specific edaphoclimatic conditions. In other words, not all practices are good everywhere and at all times. Their supposed benefits must be corroborated *a priori* for the specific agroecosystem under consideration.

Ideally, in addition to practical support regarding the most appropriate way to apply these practices depending on the specific edaphoclimatic conditions, type of crop, etc., it is desirable to provide farmers with theoretical knowledge pertaining to the underlying

causes of their potential beneficial effects on crop yield, soil health, biodiversity, etc., as well as concerning the advantages of opting for an environmentally-friendly, nature-respectful agriculture. After all, theory and praxis have a high degree of complementarity, dependence, and mutual reference. Theory grounds and enlightens praxis. Praxis often creates and backs theory (it provides the necessary empirical testability). And knowledge-based capacities and choices are deeply interrelated. Moreover, in order to change farmers' perspectives and customs, suitable governance structures and measures, progressive educational and motivational mechanisms, and ambitious yet realistic roadmaps are needed. At the moment, the agricultural world is facing a Goethean conflict between the right way and the easy way (easy way = business as usual). But to go down the right path, in addition to an ongoing commitment to training on the part of all, farmers must be involved from the start in order to design with them the most appropriate route and pace to the finish line desired by all, that is, a sustainable agriculture that provides quality and affordable food for all, while respecting nature, the integrity of the biosphere, and the functioning of the Earth system. Regenerative agriculture should not only be productive, ecological, and ethical, but also promote knowledge among farmers and agronomists. Agronomy must become an interdisciplinary science, integrating natural and social sciences, and acknowledge that agriculture poses an immense pressure on natural resources and that such pressure needs to stay within planetary boundaries (Struik and Kuyper, 2017). To this must be added the desirability of a sound ethical training that fosters responsibility and deontology. We live in an age full of fake news, sophistry, spurious manipulations, quackery, etc. in which dogma often triumphs over science. More than ever, we need to promote an agricultural enlightenment through the empowerment of farmers based on their theoretical and practical training in not only scientific but also humanistic matters. We need an eco-ethical and enlightened agrarian worldview. Farmers must acquire knowledge on the interconnectedness between the small (practices applied on the farm) and the colossal (the state of our planet). Artificial intelligence, algorithms, robotics, biotechnology, etc. will become extremely important in the coming years, and farmers must be prepared to adapt to this technological transition. We must appeal to knowledge as one of the key bets to respond to the challenges that will shape the future of agriculture and, in particular, of farmers. After all, "the cracks in knowledge are filled with ideological plaster" (aphorism by Jorge Wagensberg). Positively, the bet must be permanent, because in the acquisition of knowledge, the road ahead is always infinitely longer than the road travelled, and it is usually accompanied by an increase in perceived ignorance.

When trying to reconcile economic, environmental, and social variables, trade-offs will emerge. Trade-offs are often the focus of many of the difficult decisions that need to be taken within the sustainability arena. Often, technological innovations, if properly targeted, can reduce trade-offs. For instance, technological innovations such as precision sprayers can reduce trade-offs between agricultural yields, labour, and biodiversity conservation (Gerhards et al., 2022). It is imperative to provide farmers, as "stewards of the land," with all the tools and theoretical and practical knowledge to fully grasp the advantages and disadvantages that different technologies can bring them, so that they can make the best decisions when faced with the inevitable trade-offs. Some innovations promise hope for agricultural sustainability, but it must not be forgotten that they must always be inclusive and their application must be progressive in order to leave no one behind. It must be remembered that in many countries the average age of farmers is high.

The safe and just Earth system boundaries approach is, by definition, centered on human well-being. Then, RA should also be a socially-responsible and ethically-committed activity, implying that labour issues (burdensome physical work, labour drudgery, exposure to chemicals, salary, work conditions, race-gender-disability-ethnicity equality and equity, etc.) must be embedded in its philosophy. Among other aspects, especially in the Global South, addressing labor issues is essential to biodiversity-smart farming (Daum et al., 2023).

Many authors have previously addressed the concept of RA. In their review on the topic, O'Donoghue et al. (2022) proposed the following definition of RA: "Any system of crop and/or livestock production that, through natural complexity and with respect to its contextual capacity, increases the quality of the product and the availability of the resources agriculture depends upon: soil, water, biota, renewable energy and human endeavor." According to the Farmscape Function Framework, these authors proposed a set of indicator targets for the different dimensions of RA: (i) *soil:* OM, pH, bulk density, aggregate stability, ground cover, and nutrient profiles; (ii) *water:* soil infiltration, consistency of plant available water, stream flow consistency, and stream flow quality; (iii) *biota:* above and below ground flora and fauna diversity and abundance; (iv) *human:* income, autonomy, quality of life, and community stability; (v) *crop:* quantity and quality; and (vi) *energy:* input of fossil fuels, renewably sourced energy, fertilizers, and incidence radiation capture. O'Donoghue et al. (2022) affirmed that the process of indicator refinement needs to be iterative and rely on an IPPI—Intention, Principle, Practice, Indicator—mechanism.

Somewhat paradoxically, RA is promoted by civil society and NGOs as well as by multinational companies. In this respect, Giller et al. (2021) argue that RA represents a re-framing of what have been considered two contrasting approaches to agriculture, namely agroecology and sustainable intensification, under the same banner. Hermani (2020) considers that RA has the potential to (partially) bridge the gap between conventional and organic farming, although the opposite also holds true. Dudek and Rosa (2023) claim that RA is frequently identified with the biological farming concept (biologisation of agriculture) and understood as production based on natural methods and mechanisms, whose popularity can be ascribed to the global trend towards the sustainability of food production systems in terms of yield, environmental, and social considerations. Gordon et al. (2023) stated that RA is an attempt to build a more encompassing discourse through an alliance of smaller discourses, such as (i) restoration for profit; (ii) big picture holism; (iii) regenerative organic; (iv) regrarian permaculture; (v) regenerative cultures; (vi) deep holism; (vii) first nations; (viii) agroecology and food sovereignty; and (ix) subtle energies discourses. These authors (Gordon et al., 2022, 2023) reckon that a discourse with many unresolved tensions, such as the RA discourse, is vulnerable to co-optation and greenwashing, thus diluting its transformative potential. Sands et al. (2023) argue that the RA debate by Western culture has omitted discussions on social justice, relational values, and Indigenous and local knowledge not aligning with Western-centric, producer-consumer frameworks, despite the fact that many RA techniques have been practiced for centuries by Indigenous and local communities. These authors proposed an Indigenous-informed approach and a dynamic

anti-colonial definition of RA: "A way of farming comprised of entangled values and practices, and founded in Indigenous principles of loving-caring for the Earth. This approach to farming values (1) reciprocity, (2) respect, (3) collective (human and non-human) wellbeing, (4) knowledge co-creation, and (5) (re)localization, and it is often practiced through some combination of (1) minimizing soil disturbance, (2) maintaining vegetative soil cover, (3) maximizing diversity, (4) integrating livestock, and (5) minimizing synthetic agrichemicals." In the same line of thought, Hermani (2020) claims that the RA discourse almost exclusively addresses farming and livestock systems in highly industrialized countries. However, a replacement of agrochemical inputs by ecological methods and processes is advocated by many RA supporters, drawing from agroecology and organic farming, as well as from more marginal concepts such as holistic management and permaculture (Hermani, 2020). Regenerative agriculture has generated much buzz in the business sector as a flourishing market promising financial return and good consciousness. Some large companies are promoting RA with their own programmes, focused only on piecemeal improvements and single regenerative practices within an unchanged industrialized system (Hermani, 2020); in other words, not promoting a paradigm shift but simply marginal technical aspects of conventional forms of production and consumption (Bless et al., 2023). The approach to RA shown by some large companies can empty alternative approaches (e.g., agroecology) of political, social, symbolic and transformative content (Tittonell et al., 2022). Often, the RA narrative is biased towards commercial capitalized farmers, frequently large-scale farmers and external investors, which makes RA vulnerable to being co-opted by industry through, for example, greenwashing (Sands et al., 2023). There is the risk that these companies will only focus on the differentiation of their products in a select consumer market and not on the positive social impact.

Through a genealogical analysis of four sustainable agriculture narratives (organic agriculture, conservation agriculture, sustainable intensification, agroecology), Bless et al. (2023) revised how RA's momentum can be contextualized within existing narratives and concluded that the genealogies of the four narratives have resulted in a number of contestations and complementarities which have coalesced to drive the emergence of RA. Bless et al. (2023) observed that, in contrast to agroecology, RA shares with other narratives a limited scope for offering transformative routes for agricultural production, mainly owing to insufficient consideration of power and equity issues, reflecting the fact that it is not the unifying sustainable agriculture narrative it has claimed to be.

From all of the above, it is clear that there is much confusion and many unsettled tensions and mistrusts with the RA concept. A large part of the explanation for this is that we are still stuck in a never-ending critical debate, often not only vehement but belligerent, between ecology and economy, between production and conservation, between economic profit and social benefit, between growth and degrowth, between productivism and post-productivism, and so forth. But this is not a peculiarity of RA, it is a constant permeating many human activities, over decades and decades, with strongly politicized and polarized positions. We, of course, do not claim to have the magic wand to resolve these conflicts and debates, many of them with a strong emotional component combined with an insufficient dose of rationality. With this article, we only intend to add a new facet to the already multifaceted issue of the RA concept: the possibility of linking RA to the safe and just Earth system boundaries, in order not to forget the indispensable global perspective and the biophysical limits of human life on planet Earth. Our proposal faces the same barriers, complexities, and limitations as all those that aim to confront the challenge of reconciling the economic, environmental, and social aspects of sustainability; after all, this is the ultimate goal of RA and of all those agricultural systems that aspire to overcome, better improve, the current system of food production.

All in all, we need a RA that (i) contributes positively, as much as possible, to the concepts and paradigms presented above (especially, the safe and just Earth system boundaries); (ii) does not negatively impact the planetary boundaries; (iii) promotes soil health and minimizes soil threats (contamination, loss of OM, nutrient imbalance, compaction, erosion, loss of biodiversity); (iv) restores the structural heterogeneity of the soil (and land) and the biological processes on which its functionality depends; and (v) builds agroecosystem resilience through biodiversity and diversification. The RA paradigm must include, as much as possible, aspects related to territorial planning by raising awareness among land managers and policymakers regarding the existence of ecological corridors, the landscape heterogeneity in terms of composition and size of patches, the presence of agriculture in peri-urban areas, etc.

But it is crucial to understand that the success of RA does not only depend on how successful scientists and farmers are in identifying and applying the most sustainable practices. Instead, it largely depends on our success at generating a compelling paradigm-based fertile narrative that voluntarily changes the habits, customs, beliefs, traditions, perceptions, attitudes, ideologies, values, behavioral patterns, etc. of the agricultural world. Paper can hold anything, but if we fail in this last aspect, we will not be able to regenerate agriculture so that it can successfully adapt to the future ahead. Therefore, sociologists, psychologists, anthropologists, philosophers, historians, economists, artists, etc., must contribute their knowledge about human nature and, specifically, about the best ways to embrace and approach necessary changes and transitions. In this respect, Mario Bunge affirmed that the objectives for socio-technological endeavours are provided by ethical and socio-philosophical considerations, and that scientific knowledge only helps to implement them in an optimal way (Bunge, 1998). We scientists are aware of the many limits of our knowledge, empirical and heuristic approaches, and scientific ontological and epistemic beliefs, especially when we are asked to operate outside the pure realm of science, as it is the case of the farmers´ transition to a new vision. Actually, a new vision is probably a much more appealing term than a new paradigm. We all need a regenerative vision of agriculture and, for that purpose, we need to embark on a heuristic process of personal and collective learning. After centuries of agriculture, we have come to realize that the "puzzle" is not complete and that a theoretical and practical revolution is needed to solve it. In *The Structure of Scientific Revolutions* (1962), Kuhn argued that normal science is a puzzle-solving activity conducted under a reigning paradigm. The puzzle of sustainable agriculture has not been solved; an agricultural revolution is needed to solve this "anomaly" (*sensu* Kuhn).

Finally, Paul Feyerabend considered that the success of science is not only due to purely scientific methods, but also to the fact that science fruitfully absorbs knowledge from non-scientific sources (Feyerabend, 1975). And, in his book *Consilience: The Unity of Knowledge* (1998), Edward O. Wilson argued that "the greatest

enterprise of the mind has always been and always will be the attempted linkage of the sciences and humanities"; maybe, our preparation for a truly RA is a good opportunity to bridge the gap between the sciences and the humanities, as brilliantly defended by Charles Percy Snow in *The Two Cultures and the Scientific Revolution* (1959).

6 Conclusion

In this article, without claiming to have the ultimate answer, we have proposed to link RA with the safe and just Earth system boundaries (a framework connected to many relevant concepts today) as the basis for the generation of a paradigm that could robustly ground an appealing regenerative narrative that could nourish the vocation of a new generation of farmers and agronomists. The evaluation of the safe and just Earth system boundaries accounts for Earth system resilience and human well-being in an integrated framework, which is precisely what sustainable agriculture is all about. Our proposal connects the small (the farm) with the colossal (the Earth) in an attempt to confront one of the main sources of criticism for agriculture, i.e., its global environmental impact. The idea is to define the performance of RA in terms of its positive influence on the safe and just Earth system boundaries through its sustainable contribution to a highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, and ethically-committed agriculture. We have proposed the following definition of RA: "an approach to sustainable farming that uses soil health, biodiversity, and climate-resilient genetically-diverse crops as the basis of a highly-productive, environmentally-sound, nature- and biodiversity-respectful, socially-responsible, and ethically-committed agriculture that positively contributes to the provisioning of multiple ecosystem services and, in particular, to the safe and just Earth system boundaries." The success of RA largely depends on our success at generating a compelling paradigm-based fertile narrative that voluntarily changes the customs, beliefs, traditions, perceptions, values, etc. of the agricultural world, and, to this aim, we must absorb knowledge from the humanities.

Author contributions

CG: Conceptualization, Writing – original draft, Writing – review & editing. OU: Conceptualization, Writing – review & editing. IA: Conceptualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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