EARTH4ALL: DEEP-DIVE PAPER 13

February 2023

Regenerative agriculture for food security and ecological resilience: illustrating global biophysical and social spreading potentials

Jannes Breier*
Research associate, Potsdam Institute for Climate Impact Research, Potsdam, Germany

Luana Schwarz*
Research associate, Potsdam Institute for Climate Impact Research, Potsdam, Germany and Institute of Environmental Systems Research, University of Osnabrück, Osnabrück, Germany

Jonathan F. Donges
Research group leader, Potsdam Institute for Climate Impact Research, Potsdam, Germany and Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

Dieter Gerten
Research group leader, Potsdam Institute for Climate Impact Research, Potsdam, Germany

Johan Rockström
Director, Potsdam Institute for Climate Impact Research, Potsdam, Germany and Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

DOI: 10.48485/pik.2023.001

Earth 4All

Abbreviations:

CA	Conservation agriculture
CF	Conventional farming
CoP	Community of practice
PBs	Planetary boundaries
RA	Regenerative agriculture
SES	Social-ecological system
SI	Sustainable intensification

Introduction

Agriculture has been closely interwoven with human development for centuries and is now a core issue of the Anthropocene. The Neolithic (first agricultural) Revolution, and later the Green Revolution, transformed nature into a cultivated landscape and decisively shaped social landscapes, thus creating the basis for our modern society.

The Green Revolution in the 1950s and 1960s led to a significant increase in productivity through modern machinery, artificial fertilisers and highly bred crop varieties (Evenson & Gollin, 2003). At the same time, the impact on the environment, including on soils, water quality and biodiversity, has often been neglected. As the world's population and the demand for agricultural products is growing further, the environmental impacts are not only becoming more acute, but also have long-term implications for food security itself. Global food systems will remain highly dependent on ecosystem services and abiotic factors, some of which are also changing for the worse, most notably climate (Foley et al., 2005; Wheeler & von Braun, 2013).

The planetary boundaries (PBs) framework (Rockström et al., 2009; Steffen et al., 2015) provides a coherent global-scale reference system to quantify the overall influence of these environmental impacts on the Earth system and on human societies. It defines boundaries for nine Earth system processes – among them climate change, freshwater use, land-system change and changes in biogeochemical flows such as nitrogen and biosphere integrity – which together demarcate a Holocene-like Earth status. The underlying normative, precautionary principle of the framework is that the PBs should not be transgressed. Otherwise, we threaten the safe operating space for humanity, and risk tipping the Earth onto a trajectory that departs significantly from Holocene conditions (which have enabled the emergence and sustenance of a human civilisation with billions of people) to minimise the risk of large-scale disruptions and destabilisation of our planet.

Modern practices of **conventional farming (CF)** are placing increasing pressure on many of the PBs; indeed, agriculture is the main driver of current PB transgressions (Campbell et al., 2017; Gerten et al., 2020). For example, CF practices compromise the integrity of the (terrestrial) biosphere through the cultivation of large monocultures and invasive tillage. Degradation of soils and other resources, such as freshwater influenced by nutrient leaching, leads to changes in the natural flow regime of rivers. Processes such as water extraction for irrigation of agricultural land have serious consequences for the aquatic and adjacent terrestrial ecosystems (Gerten et al., 2013), and represent transgressions of the freshwater

PB. Agricultural practices can also adversely affect the status of the freshwater PB through changes in soil moisture. Tillage and soil degradation lead to a constant reduction in soil water-holding capacity and net losses in root-zone soil moisture (Wang-Erlandsson et al., 2022).

> **It is essential to increase productivity on the already existing agricultural land – to ensure food security while not putting Earth stability at further risk**

Moreover, the widespread introduction of artificial fertilisers into a previously balanced nutrient cycle has greatly changed cultural and natural landscapes, with negative consequences for biodiversity, the climate (contributing to climate change through greenhouse gas emissions) and soil and water quality (Baessler & Klotz, 2006; Foley et al., 2005).

A further terrestrial PB directly affected by agricultural practices is land-system change, via conversion of natural areas into arable land at the cost of large contiguous ecosystems that are important for many functions of the Earth system. To stay within this and the other PBs, and to potentially reverse its current transgression, it is essential to increase productivity on the already existing agricultural land – to ensure food security while not putting Earth stability at further risk (Campbell et al., 2017).

In this article, we provide a preliminary analysis of the potential effects on soil ecology and crop yield of a global-scale transition to regenerative agriculture. Previous analyses have only focused on the biophysical potential of resource-efficient measures for increasing global agricultural production (Gerten et al., 2020; Springmann et al., 2018). Here, we quantitatively and conceptually advance the field by also considering potential social spreading dynamics that actually determine whether – and to what extent – farmers would adopt such practices. Although 11% of the world's population are farmers, agriculture does not provide a good/stable livelihood for many. Economically, farmers are often dependent on government subsidies and have fluctuating incomes. This is due to numerous factors, such as the high cost of fertilisers, dependence on certain types of grains and unstable markets for their produce. In some regions, changing climatic conditions are altering the farmers' environment to the extent that they must abandon their land because the soils are no longer fertile enough to be viable.

Sustainable agriculture

To overcome the negative consequences of conventional farming, alternative approaches have arisen in recent decades. These are often subsumed under the term sustainable agriculture, defined by the Food and Agriculture Organization (FAO) as " ... the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development ... conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (FAO, 1989, p. 65).

Various approaches have been developed and implemented to achieve this transformation (Oberč & Arroyo Schnell, 2020). One established approach is **conservation agriculture (CA)**, which has its roots in conservation tillage as a solution that emerged from the “Dust Bowl” that affected US and Canadian prairies in the 1930s (Hobbs, 2007). In the 1970s and 1980s, this approach was complemented by the practice of intercropping and crop rotations and has been employed widely under the label CA since the 1990s. The FAO highlights three key principles of CA:

- Minimisation of soil disturbances
- Enhancement or maintenance of a protective organic cover
- Cultivation of a wide range of plant species (FAO, 2011).

Over the years, CA has proved capable of halting and even reversing soil degradation, thus regenerating soil quality. Due to its historical origins in North and South America, CA is already widespread in these regions, while in Europe it is still mainly a niche activity. Part of the reason for this are the high upfront costs: converting land to CA is expensive, so are the required machines, so it must be possible to amortise the investment accordingly. In addition, yields are sometimes lower in the first few years and will only improve if certain conditions are available (Pittelkow et al., 2015). For decades, subsidies have helped farmers in the United States to implement CA.

Nevertheless, CA has a number of advantages, such as the reduction of machinery use with savings especially in fuel consumption, the reduced use of expensive artificial fertiliser, and the higher resilience of CA to anthropogenic climate change compared with CF (Michler et al., 2019). An intelligent application of CA’s three core principles can also reduce the use of pesticides and herbicides; in particular, the right choice of cover and crop rotations plays a decisive role (Nichols et al., 2015; Pretty et al., 2006). Through these positive effects, CA can potentially reduce the strains on different PBs, especially those for freshwater and biogeochemical flows.

CA forms a basis for many other sustainable agriculture approaches, as does **regenerative agriculture (RA)**, which was developed in the 1980s and shares CA’s principles for soil health. For instance, RA is also strict about the use of pesticides and herbicides, both of which are kept to a minimum. Where RA diverges is its broader focus on increasing biodiversity in general and creating a closed nutrient cycle in combination with livestock management at farm level. It includes additional approaches such as manure composting, rotational grazing and silvopasture in grassland management (Smith et al., 2021). In practice, RA and CA involve similar cropping systems and the terms are often used interchangeably. Some scholars and practitioners additionally ascribe a social dimension to RA (Müller, 2020). Some of the more holistic regenerative approaches transcend soil regeneration and additionally aim at “regenerating” the social aspects related to agriculture. For example, in terms of good livelihoods, social relationships and stable incomes (LaCanne & Lundgren, 2018), future perspectives, and (re) building human–nature relationships (E. Gordon et al., 2022; Hes & Rose, 2019).

Social mechanisms of a land-use transformation

Agricultural systems are intrinsically social–ecological (L. J. Gordon et al., 2017; Meyfroidt, 2013). That is why a transformation towards agricultural systems respecting PBs while supporting livelihoods cannot be understood and enabled without considering the deeper societal processes driving the change. Developments in the emerging and transdisciplinary field of "transition studies" address the question of how such profound change can come into being (Holtz et al., 2015; Olsson & Galaz, 2012; Walker et al., 2004). Within the sub-field of land system transitions, scholars have highlighted the broad variety of drivers in additional to economic dynamics (Burton et al., 2020; Dessart et al., 2019; Maybery et al., 2005). While economic elements are certainly important, we focus on social contagion, social learning and social tipping points. We deem this to be a relevant lens for understanding diverse characteristics of transformative change (Conley & Christopher, 2001; Schneider et al., 2009).

Social contagion is a concept that helps to understand the phenomenon of novel practices, behaviours, opinions or ideas spreading in social networks (Lehmann & Ahn, 2018; Tsvetkova & Macy, 2014). It originates in the "theory of diffusion of innovations" postulated by Everett Rogers (1962), and in modern applications encompasses diverse forms of interaction-based contagion processes (Peres et al., 2010). Rogers described the agents picking up a novel trait in early stages as the system's "innovators" and "early adopters". During a social contagion process, a certain trait, for example regenerative farming behaviour, is passed from these "early acting agents" to another agent in one's social network (to a certain probability, depending on their susceptibility). Scholars distinguish between simple and complex contagion; while both can be helpful for understanding such processes, the adoption of RA cannot be expected to spread like a virus or a piece of information, as a simple contagion process would suggest (Centola & Macy, 2007). The adoption of novel opinions and behaviour is better understood as complex contagion, implying the necessity of several interactions with novel practices for behavioural change (Kitzmann et al., 2022), such as via continuous interactions with one's social environment, or in social learning contexts.

There is ample evidence that individuals tend to coordinate with others or to conform to the social norms that are prevalent in the social groups and networks they are associated with (Bicchieri, 2016; Centola et al., 2018; Farrow et al., 2017; Nyborg et al., 2016). Conformity to social norms has many underlying mechanisms. It may be driven by fear of sanctions or a desire to do what is socially acceptable, perceived benefits to coordinating with others, and information implicit in social norms about what works or what is appropriate in certain contexts.

Social learning describes a class of related mechanisms that can be seen as the foundation of social contagion processes (Reed et al., 2010). For example, imitation of a successful strategy or practice can be classified as a form of "single-loop learning": a process of behavioural change and improvement of action strategies with the aim to reach better outcomes, without necessarily challenging underlying assumptions, concepts, theories or value systems on the basis of which a given decision was made (Pahl-Wostl, 2009). In the context of RA, this could manifest as the adoption of RA practices to increase farm profitability through carbon capture credits or payments for ecosystem services. In contrast, behavioural changes driven by changes more deeply anchored in individual value systems can be conceptualised as double- and triple-loop learning processes (Gupta, 2016).

Double-loop learning involves questioning variables, such as underlying goals, assumptions, problem framing, and individual priorities. For instance, this could be an action taken by a farmer who has asked themselves: do I want my agricultural practices geared towards maximising yields, or building up humus for healthier soils? In a triple-loop learning process, a learner proceeds one step further and additionally questions values and normative beliefs underlying those factors, which in turn can lead to an adjustment of one's world views (Tosey et al., 2012). Therefore, triple-loop learning has the potential to alter human–nature relationships at a deep level, as well as reshape the "reference framework" considered when laying out an action strategy. A sense of deeper connectedness with one's land, as sketched in the concept of "environmental stewardship", can be regarded as an outcome of a triple-loop learning process and act as a foundation for novel land-use decisions. Individually held values regarding a given farming practice have been found to impact land-use style (Dessart et al., 2019; Gosnell et al., 2019). Value shifts can be facilitated through networks and group contexts, such as farmer communities of practice (CoPs) like Costa Rica Regenerativa or the Climate Farmers.

Learning processes can take place locally and non-locally. Direct exposure to a novel farming system (e.g., by means of a neighbouring farm) can be the decisive factor (Schneider et al., 2009), but geographical proximity is not a necessary precondition for learning to take place. For example, CoPs can act as social networks connecting farmers and thereby providing learning spaces non-locally (Conley & Christopher, 2001; Morgan, 2011; Wenger, 1998). Another example is the influence that family members living abroad can have on a farmer's decisions, which is observed in Laos where Laotian relatives living in the diaspora had a decisive impact on rubber tree adoption in their original homeland (Junquera et al., 2020). Social learning processes have the potential to shape the learning environment, and could consequently have an impact on the social fabric of institutions, practices and norms. In turn, this deep impact could be an important accelerator for social tipping points.

Social tipping points can be critical levers within a social system as, when systematically targeted through certain interventions, they could trigger rapid social transitions (Otto et al., 2020; Winkelmann et al., 2022). On the one hand, purely social or socioeconomic tipping points can be identified (Doyle et al., 2016); same-sex marriage acceptance or the condemnation of smoking in public places are examples (Nyborg et al., 2016). On the other hand, within social–ecological systems research, there is the additional criterion of social shifts being linked to change in the ecological system (Milkoreit et al., 2018). Climate change mitigation has to date been at the centre of social tipping point research (Otto et al., 2020); however, the concept has also been applied to agricultural transitions (Smith et al., 2021).

Taken together, the concepts of social contagion, social learning and social tipping processes create a perspective of well-documented and well-investigated societal transition dynamics. They offer new ways of thinking about how agricultural systems could be transformed to more sustainable and regenerative approaches – at individual, societal and even global levels. Such concepts complement the purely biophysical aspects of transitions, by considering the social dynamics that could drive their implementation in the real world.

Simulating a giant leap in agriculture

Following Earth4All's overall transformative Giant Leap scenario (Dixson-Decleve et al., 2022), rapid change is needed, especially in agriculture, to transform the current mostly conventional farming systems into sustainable ones. To restore soil health and maintain food security in a rapidly changing global climate, measures such as those described in that scenario must be implemented quickly. Dietary habits can adapt comparatively quickly following changing social norms, while equilibrium processes in the biosphere, especially plant–soil interactions, can take comparatively long periods of time as a result of changes in agricultural management (Herzfeld et al., 2021a). Here, we simulate an idealised global transition, analogously referred to as the *Giant Leap*, parameterised as a step change within one year (2022) from CF to RA, assuming that RA practices are applied worldwide immediately (see Table 1). Our study uses the dynamic global vegetation and crop model LPJmL (Schaphoff et al., 2018; von Bloh et al., 2018). This preliminary analysis aims to roughly indicate the biophysical potential of a transition to RA in reducing the anthropogenic pressure on the terrestrial PBs that are being transgressed due to widespread conventional agricultural practices. The study extends an earlier analysis (involving a previous version of LPJmL) that showed how efforts to sustainably intensify agriculture can feed a global population of 10 billion within the PBs (Gerten et al., 2020). New features and management options enable us to focus attention on soil health and its wider implications for ecosystem resilience and food security (Lutz et al., 2019; Porwollik et al., 2021). Table 1 summarises the options relating to tillage, residue removal and crop covering within the *Too Little Too Late* and *Giant Leap* scenarios. Future climate change is not considered; instead, the last 10 years of climate inputs up to 2019 are repeated until 2035, as additional climate change would amplify several impacts and include additional feedbacks, making it difficult to assign to the underlying problem in each case (Herzfeld et al., 2021b).

Scenario	Timespan (years)	Tillage	Crop residue management	Cover cropping	Climate scenario
Too Little Too Late	1901–2035	Conventional tillage	Residue removal	No cover cropping	No additional future climate forcing
Giant Leap	2022–2035	No tillage	No residue removal	Cover cropping	No additional future climate forcing

Table 1. The *Too Little Too Late* and *Giant Leap* scenarios simulated by LPJmL, with the *Giant Leap* diverting from *Too Little Too Late* in 2022 with a global transition to RA with the listed measures.

Biophysical effects of regenerative agriculture

One effect seen in the model is that soil evaporation quickly decreases when soil cover by plant litter increases after harvest. Soils contain higher moisture levels, including root-zone soil moisture – making more water available to the plants. Transpiration also increases in many areas as a result of water uptake, and the rates are even higher when crops are cultivated in given areas. The net impact on soil moisture therefore varies depending on the prevailing conditions in any given region, though most regions do see higher plant-available soil moisture. On a global scale we find a net increase in root-zone soil moisture of about 4.3% on all land in the *Giant Leap* compared with *Too Little Too Late*. This makes conservation agriculture a suitable countermeasure in regions where transgressions in the Green Water PB in terms of dry baseline departures can be observed (Wang-Erlandsson et al., 2022).

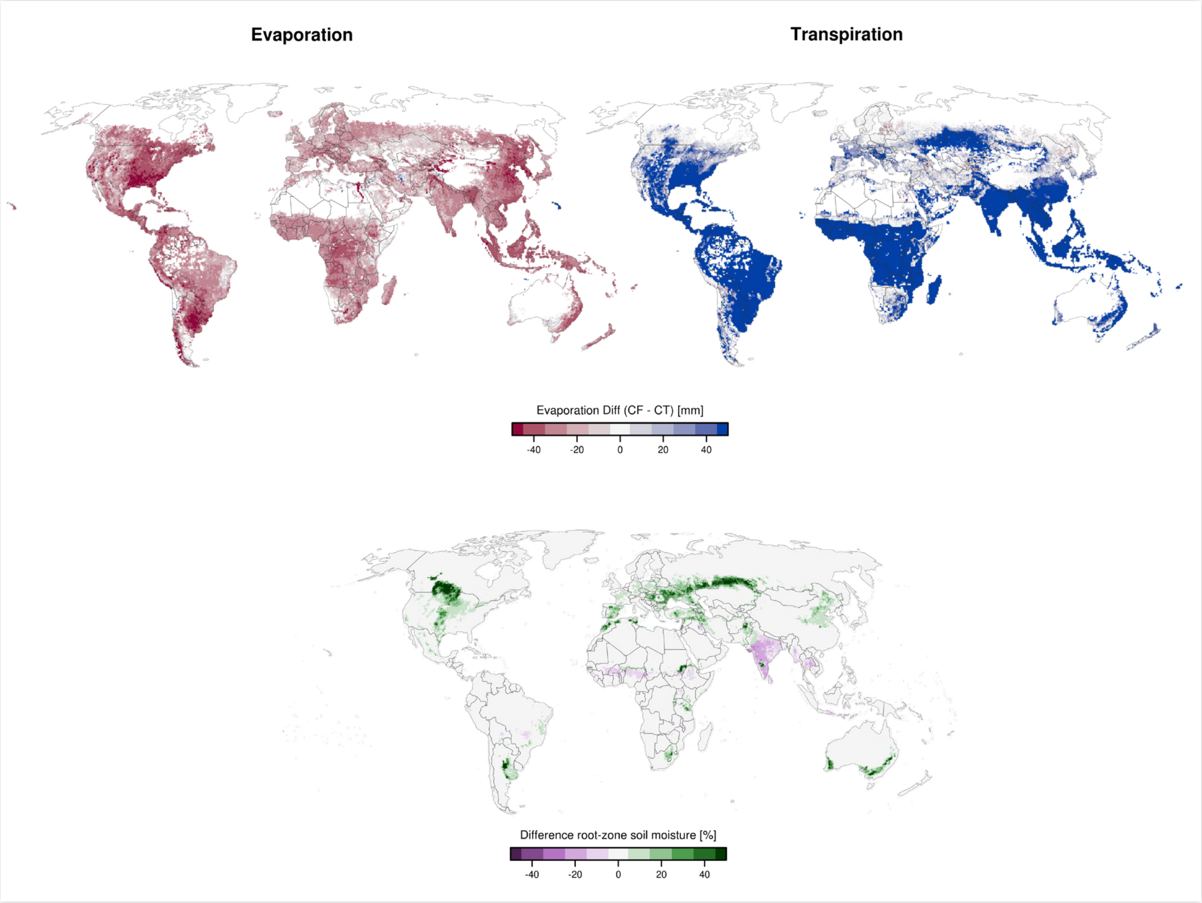

Figure 1. Evaporation and transpiration flux changes (in %) and corresponding difference in the root-zone soil moisture on agricultural land of the *Giant Leap* over *Too Little Too Late* for simulation year 2035, simulated by LPJmL.

In addition to water fluxes, carbon fluxes are also simulated to change considerably. The assumed constant soil cover and absence of any soil turnover leaves soil less exposed to the atmosphere, whereby less carbon is oxidised and thus emitted as CO2. The additional crop residue/litter biomass shifts the balance of soil carbon processes in favour of a temporary accumulation of soil organic carbon.

As a result, the soil carbon stocks start to increase already in the first years after the simulated global transition to RA compared with *Too Little Too Late*. Increases are especially pronounced in the tropics as well as in presently intensively farmed areas such as the eastern United States, India or Eastern China as shown for the year 2035 (with constant climate) in Figure 2. Already by 2035, after 13 simulation years in our stylised experiment, cumulative carbon sequestration would thus reach a global total of about 26 GtC in the *Giant Leap* scenario.

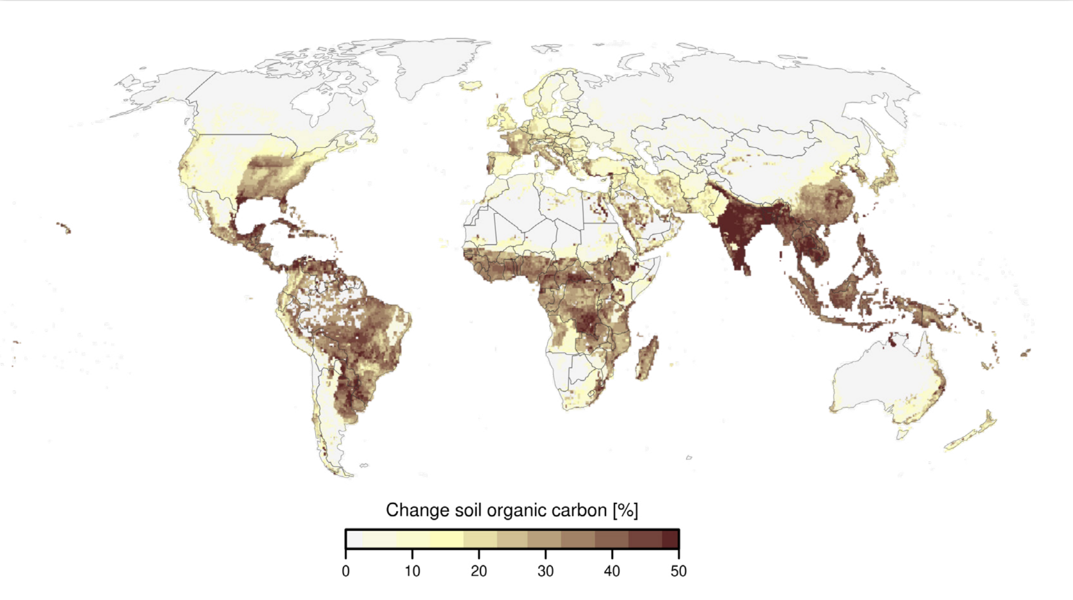

Figure 2. Soil carbon increase on agricultural land of the *Giant Leap* over *Too Little Too Late* for the year 2035.

An increase in the amount of soil carbon has several effects on the soil. It is an indicator for the increase of micro- and macro-organisms in the soil, and for the general increase of the water-holding capacity (as an additional benefit for a net increase in root-zone soil moisture) and the fertility of the soil (Stockmann et al., 2013). Soil biodiversity increases thanks to the undisturbed natural soil structure and the long-term naturally grown soil organic matter under no-till conditions (Palm et al., 2014). Ecological resilience increases via the interplay of these factors, especially in the face of climate change (Michler et al., 2019).

Boosting soil fertility is a key to compensating for the negative yield effects of not tilling the soil, especially within the first years and in humid regions. Figure 3 shows that high yield increases are simulated to occur mainly in drier regions where water is scarce and therefore reducing evaporation has a great benefit. Even though these simulations do not take into account the far-reaching impacts of climate change, it can be expected that a more resilient land-use system will perform better under more extreme climate conditions (Herzfeld et al., 2021b; Jägermeyr et al., 2016).

In the *Giant Leap* some tropical regions show a negative effect on the yield where water-saving effects play a minor role and fertilisation is historically low, which is also in line with findings in other studies (Cusser et al., 2020). Cover crops in LPJmL are currently parameterised only as catch crops, that rather take up nitrogen instead of fixing additional nitrogen and passing it on to the main crops in mineralised form during decomposition, which is why positive effects from green manure might be underestimated in the simulations. Positive effects could be achieved by fixing additional atmospheric nitrogen and making it plant available in the beginning of the main season, which the current cover crop implementation does not simulate. Nevertheless, the overall global effect is positive with a net yield increase of about 5%, mainly due to the increases in dry areas such as the western United States, Spain or South Africa indicating that RA has a higher resilience to drought stresses potentially triggered by climate change.

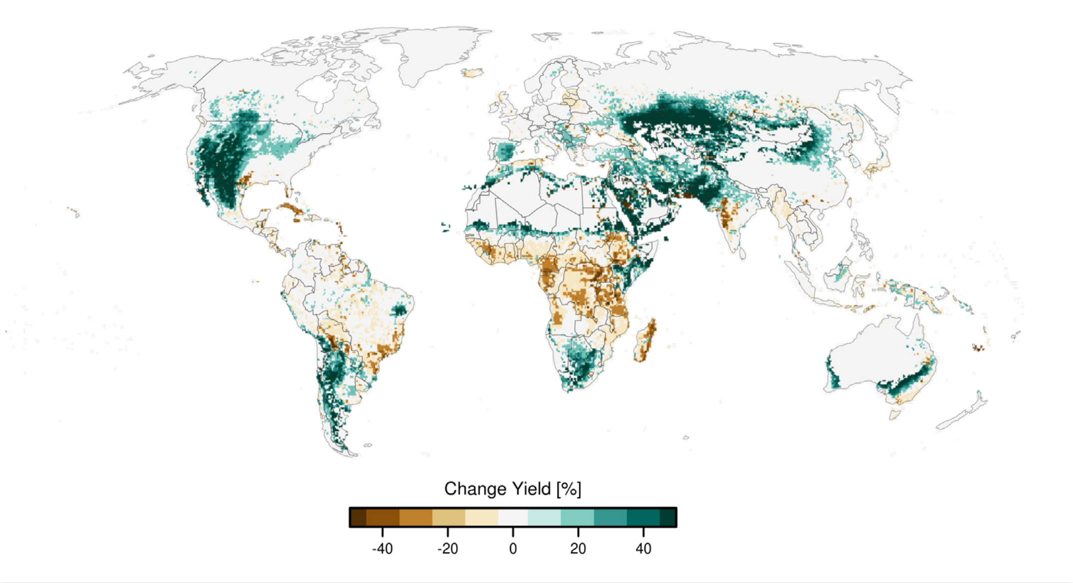

Figure 3. Simulated yield changes in the *Giant Leap* compared with *Too Little Too Late* for 2035.

Social spreading dynamics – conceptualising how a turnaround to regenerative agriculture could unfold

The above spatially detailed – if highly hypothetic – modelling results draw a promising picture of the large potential that could be unlocked with a widespread transformation of existing, conventional agricultural practices towards RA systems. However, as in many previous scenarios without explicit representation of social dynamics, they assume an immediate, worldwide "*Giant Leap* switch" whereby every farmer in the world would adopt RA practices irrespective of their current technological, economic, social and political setting. In reality, these transformations would be driven by social-cultural-political-economic dynamics, which evolve over time. They can be partly conceptualised (and eventually quantified) by the concepts of social contagion, learning and tipping points described above.

There are certain world regions, mainly in the Americas, where CA as a practice is already widely accepted as a social norm in agriculture (see Figure 4). These regions, depicted in light green, can act as seeds of change, i.e. as pioneering places of social contagion and diffusion of innovation, from which RA can spread to other regions and farmers.

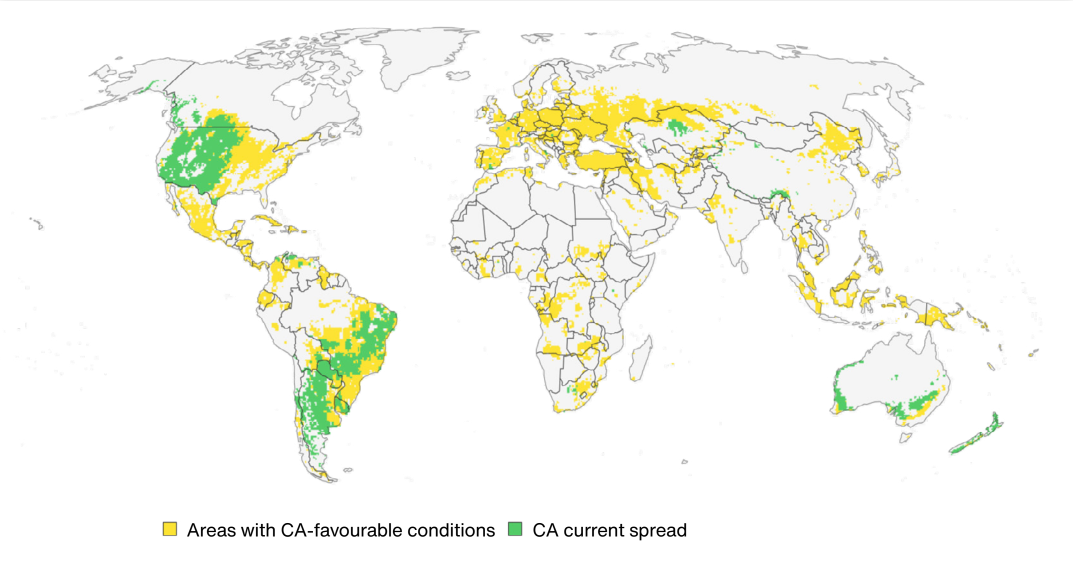

Figure 4. The yellow colours show areas in which the conditions for RA are favourable, and that have therefore been assessed as having a high likelihood for RA adoption. These conditions are based both on biophysical (humidity, crop types, water erosion) and social-ecological (farmer field size and income) factors. Spatial information of the conditions illustrated here stem from Porwollik et al. (2021).

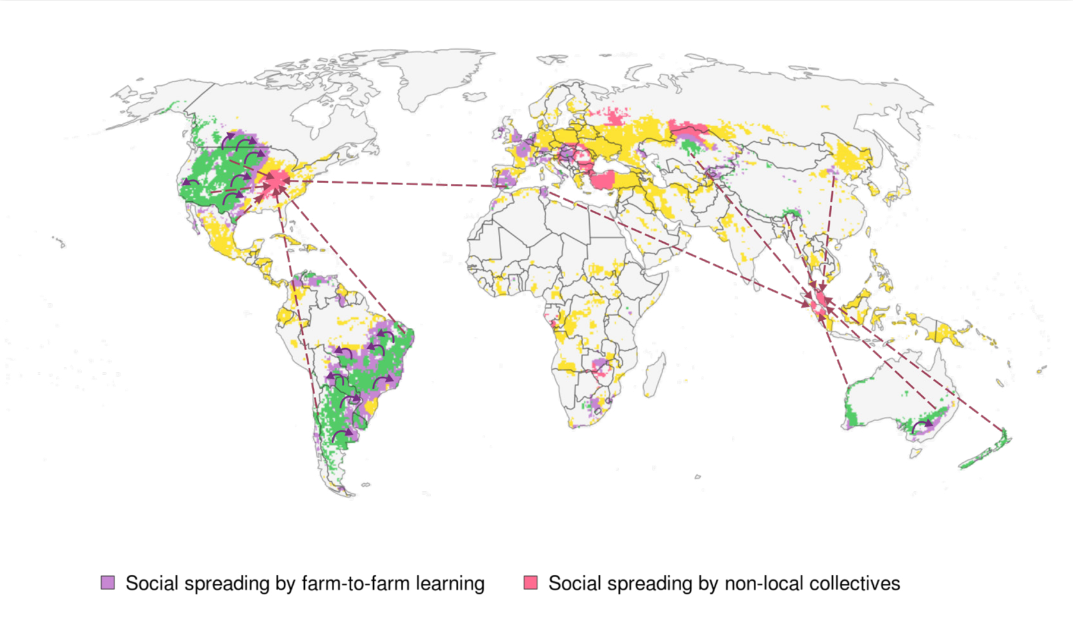

Figure 5. Adjacent areas of CA-dominated localities that have a high likelihood of CA adoption through local learning processes (purple, with curved arrows), areas potentially subject to CA adoption through to non-local spreading processes (pink, with dashed arrows). Both trends for illustrative purposes only. The arrows indicate the direction of spread for selected examples.

The purple areas in Figure 5 depict neighbouring regions of current RA-dominated areas with supportive conditions for RA (i.e. yellow-zone regions that have borders with green zones). These purple-coloured areas are candidates for the adoption of RA through local spreading and contagion processes, such as social norm compliance-driven imitation or experimental social learning, for example by visiting neighbouring farms and witnessing the feasibility and advantages of RA first hand.

The pink colour in Figure 5 highlights that such spreading processes are not only limited to happening locally between neighbouring farms, but can also take place in a region or over even larger scales. They highlight examples of where RA could spread through non-local processes and social networks. International organisations and social farmer networks/CoPs provide non-locally bound spaces for exchange and social learning, and therefore non-local spreading of RA. Both purple and pink areas are illustrations of possible spreading outcomes through local and non-local mechanisms. They are not underpinned by spatially resolved empirical data but illustrate the spreading potential based on case studies and the theories of change introduced above.

One example for both local and regional spreading processes is seen in West Africa, facilitated by Warc, an organisation with agricultural production and consulting services. Beginning operations of RA in Sierra Leone, the Warc group quickly won over more smallholder farmers in the region through extension programmes. Now, they operate over 5,000 ha in Sierra Leone and Ghana in cooperation with over 1,000 smallholder farmers. The success of the system strengthens their appeal: in Sierra Leone, they managed to sustain productive farming seasons without irrigation, using mainly crop-rotations and minimal soil disturbance. Other comparable organisations are the Rodale Institute and the Savory Institute (2022), which have worldwide regional hubs and offer training, workshops and extensionist services. Networks such as the Climate Farmers and Costa Rica Regenerativa have a similar approach, but put a special emphasis on connecting regenerative farmers and farms that already exist.

If the system is ripe for change, the regenerative agriculture movement can potentially reach a social tipping point, which could accelerate widespread system change in agriculture

The concepts introduced in this article can help RA to spread through a variety of processes. To gain momentum over a larger scale, the transition also requires support from the surrounding conditions. For instance, it depends on the farmers' political and institutional embeddedness, public opinion and the economic situation, and it might also be triggered by landscape-level system shocks such as the aforementioned Dust Bowl. If the system is ripe for change, the RA movement can potentially reach a social tipping point, which could accelerate widespread system change in agriculture – even beyond that provisionally illustrated in Figures 4 and 5 (Smith/Donges et al., in prep).

We aim to represent these different spreading processes using a model that links LPJmL (simulating biophysical changes and potentials as shown above) to an agent-based model of farmer social dynamics using the copan:CORE framework (Donges et al., 2020). Within the model, farmers are the agents of change, with an option of practising RA or CF, based on observing their neighbours' strategies, interacting with them and learning from them according to the different (alternative) spreading principles presented above. LPJmL subsequently calculates how harvests and biophysical conditions will change at each site, and whether and to what extent farmers' choices will help to maintain local and global planetary boundaries. These results finally inform farmers' decision-making simulated in the agent-based model. This coupled modelling investigates spreading and adoption dynamics of RA beyond theoretical and qualitative foundations, and will complement the pure biophysical assessments of hypothetical potentials found in earlier global simulation studies (Gerten et al., 2020). Such assessments are central to operationalising knowledge about the benefits of RA systems and applying it to the real world.

Conclusion

In this deep dive, we have illustrated the potential of RA to address some of the most urgent challenges of our time in social–ecological land systems. Restoring and conserving healthy soils and creating resilient farming systems to provide food security, while adapting to climate change impacts such as droughts and extreme weather events, are central to a global food systems turnaround. Extending from the biophysical analysis, we also highlight the importance of social dynamics relating to the adoption of RA, and we lay out the potential of social contagion, social learning and social tipping points for a widespread land-use transformation. Finally, we stress the need to provide enabling conditions for RA practices to spread effectively.

In reality, the surrounding factors and conditions can also prove to be obstacles to such transformations: elements such as economic, institutional and political constraints, and distorted power structures manifested, for example, in a strong lobby of large conventional agri-food corporations, can hinder far-reaching transformative change. The potential of social diffusion processes thus depends on the institutional, political and economic climate in which they unfold. For this reason, the drivers of change are clearly not limited to farmers and their individual learning processes, but are distributed across individual actors and larger structures, which consequently also bear significant responsibility for supporting such transition processes.

References

Baessler, C., & Klotz, S. (2006). Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agriculture, Ecosystems & Environment*, 115(1), 43–50. https://doi.org/10.1016/j.agee.2005.12.007

Bicchieri, C. (2016). *Norms in the Wild: How to Diagnose, Measure, and Change Social Norms*. Oxford University Press.

Burton, R. J. F., Forney, J., Stock, P., & Sutherland, L.-A. (2020). *The Good Farmer: Culture and Identity in Food and Agriculture*. Routledge. https://doi.org/10.4324/9781315190655

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, 22(4). https://www.jstor.org/stable/26798991

Centola, D., Becker, J., Brackbill, D., & Baronchelli, A. (2018). Experimental evidence for tipping points in social convention. *Science* (New York, N.Y.), 360(6393), 1116–1119. https://doi.org/10.1126/science.aas8827

Centola, D., & Macy, M. (2007). Complex contagions and the weakness of long ties. *American Journal of Sociology*, 113(3), 702–734. https://doi.org/10.1086/521848

Conley, T., & Christopher, U. (2001). Social learning through networks: The adoption of new agricultural technologies in Ghana. *American Journal of Agricultural Economics*, 83(3), 668–673. https://doi.org/10.1111/0002-9092.00188

Cusser, S., Bahlai, C., Swinton, S. M., Robertson, G. P., & Haddad, N. M. (2020). Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. *Global Change Biology*, 26(6), 3715–3725. https://doi.org/10.1111/gcb.15080

Dessart, F. J., Barreiro-Hurlé, J., & van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: A policy-oriented review. *European Review of Agricultural Economics*, 46(3), 417–471. https://doi.org/10.1093/erae/jbz019

Dixson-Decleve, S., Gaffney, O., Ghosh, J., Randers, J., Rockstrom, J., & Stoknes, P. E. (2022). *Earth for All: A Survival Guide for Humanity*. New Society Publishers.

Donges, J. F., Heitzig, J., Barfuss, W., Wiedermann, M., Kassel, J. A., Kittel, T., Kolb, J. J., Kolster, T., Müller-Hansen, F., Otto, I. M., Zimmerer, K. B., & Lucht, W. (2020). Earth system modeling with endogenous and dynamic human societies: The copan:CORE open World–Earth modeling framework. *Earth System Dynamics*, 11(2), 395–413. https://doi.org/10.5194/esd-11-395-2020

Doyle, C., Sreenivasan, S., Szymanski, B. K., & Korniss, G. (2016). Social consensus and tipping points with opinion inertia. *Physica A: Statistical Mechanics and Its Applications*, 443, 316–323. https://doi.org/10.1016/j.physa.2015.09.081

Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science*, 300(5620), 758–762. https://doi.org/10.1126/science.1078710

FAO. (1989). *The State of Food and Agriculture*. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/t0162e/t0162e.pdf

FAO. (2011). *Save and Grow. A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome (Italy) FAO. http://www.fao.org/docrep/014/i2215e/i2215e00.htm

Farrow, K., Grolleau, G., & Ibanez, L. (2017). Social norms and pro-environmental behavior: A review of the evidence. *Ecological Economics*, 140, 1–13. https://doi.org/10.1016/j.ecolecon.2017.04.017

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. *Science*, 309(5734), 570–574. https://doi.org/10.1126/science.1111772

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., & Schellnhuber, H. J. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability*, 3(3), 200–208. https://doi.org/10.1038/s41893-019-0465-1

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., & Pastor, A. V. (2013). Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Current Opinion in Environmental Sustainability*, 5(6), 551–558. https://doi.org/10.1016/j.cosust.2013.11.001

Gordon, E., Davila, F., & Riedy, C. (2022). Transforming landscapes and mindscapes through regenerative agriculture. *Agriculture and Human Values*, 39(2), 809–826. https://doi.org/10.1007/s10460-021-10276-0

Gordon, L. J., Bignet, V., Crona, B., Henriksson, P. J. G., Holt, T. V., Jonell, M., Lindahl, T., Troell, M., Barthel, S., Deutsch, L., Folke, C., Haider, L. J., Rockström, J., & Queiroz, C. (2017). Rewiring food systems to enhance human health and biosphere stewardship. *Environmental Research Letters*, 12(10), 100201. https://doi.org/10.1088/1748-9326/aa81dc

Gosnell, H., Gill, N., & Voyer, M. (2019). Transformational adaptation on the farm: Processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. *Global Environmental Change*, 59, 101965. https://doi.org/10.1016/j.gloenvcha.2019.101965

Gupta, J. (2016). Climate change governance: History, future, and triple-loop learning? *WIREs Climate Change*, 7(2), 192–210. https://doi.org/10.1002/wcc.388

Herzfeld, T., Heinke, J., Rolinski, S., & Müller, C. (2021a). Soil organic carbon dynamics from agricultural management practices under climate change. *Earth System Dynamics*, 12(4), 1037–1055. https://doi.org/10.5194/esd-12-1037-2021

Herzfeld, T., Heinke, J., Rolinski, S., & Müller, C. (2021b). Soil organic carbon dynamics from agricultural management practices under climate change. *Earth System Dynamics*, 12(4), 1037–1055. https://doi.org/10.5194/esd-12-1037-2021

Hes, D., & Rose, N. (2019). Shifting from farming to tending the earth: A discussion paper. 21. https://www.researchgate.net/publication/335441282_Shifting_from_farming_to_tending_the_earth_A_discussion_paper

Hobbs, P. R. (2007). Conservation agriculture: What is it and why is it important for future sustainable food production? *The Journal of Agricultural Science*, 145(2), 127. https://doi.org/10.1017/S0021859607006892

Holtz, G., Alkemade, F., de Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J., & Ruutu, S. (2015). Prospects of modelling societal transitions: Position paper of an emerging community. *Environmental Innovation and Societal Transitions*, 17, 41–58. https://doi.org/10.1016/j.eist.2015.05.006

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., & Rockström, J. (2016). Integrated crop water management might sustainably halve the global food gap. *Environmental Research Letters*, 11(2), 025002. https://doi.org/10.1088/1748-9326/11/2/025002

Junquera, V., Meyfroidt, P., Sun, Z., Latthachack, P., & Grêt-Regamey, A. (2020). From global drivers to local land-use change: Understanding the northern Laos rubber boom. *Environmental Science & Policy*, 109, 103–115. https://doi.org/10.1016/j.envsci.2020.04.013

Kitzmann, N. H., Romanczuk, P., Wunderling, N., & Donges, J. F. (2022). Detecting contagious spreading of urban innovations on the global city network. *The European Physical Journal Special Topics*, 231(9), 1609–1624. https://doi.org/10.1140/epjs/s11734-022-00470-4

LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative agriculture: Merging farming and natural resource conservation profitably. *PeerJ*, 6, e4428. https://doi.org/10.7717/peerj.4428

Lehmann, S., & Ahn, Y.Y. (2018). *Complex Spreading Phenomena in Social Systems*. Springer. https://link.springer.com/book/10.1007/978-3-319-77332-2

Lutz, F., Herzfeld, T., Heinke, J., Rolinski, S., Schaphoff, S., von Bloh, W., Stoorvogel, J. J., & Müller, C. (2019). Simulating the effect of tillage practices with the global ecosystem model LPJmL (version 5.0-tillage). *Geoscientific Model Development*, 12(6), 2419–2440. https://doi.org/10.5194/gmd-12-2419-2019

Maybery, D., Crase, L., & Gullifer, C. (2005). Categorising farming values as economic, conservation and lifestyle. *Journal of Economic Psychology*, 26(1), 59–72. https://doi.org/10.1016/j.joep.2003.10.001

Meyfroidt, P. (2013). Environmental cognitions, land change, and social–ecological feedbacks: An overview. *Journal of Land Use Science*, 8(3), 341–367. https://doi.org/10.1080/1747423X.2012.667452

Michler, J. D., Baylis, K., Arends-Kuenning, M., & Mazvimavi, K. (2019). Conservation agriculture and climate resilience. *Journal of Environmental Economics and Management*, 93, 148–169. https://doi.org/10.1016/j.jeem.2018.11.008

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., Mathias, J.-D., Rocha, J. C., Schoon, M., & Werners, S. E. (2018). Defining tipping points for social-ecological systems scholarship—An interdisciplinary literature review. *Environmental Research Letters*, 13(3), 033005. https://doi.org/10.1088/1748-9326/aaaa75

Morgan, S. L. (2011). Social learning among organic farmers and the application of the Communities of Practice Framework. *The Journal of Agricultural Education and Extension*, 17(1), 99–112. https://doi.org/10.1080/1389224X.2011.536362

Müller, E. (2020). Regenerative development as natural solution for sustainability. *The Elgar Companion to Geography, Transdisciplinarity and Sustainability*, 201–218. https://doi.org/10.4337/9781786430106.00021

Nichols, V., Verhulst, N., Cox, R., & Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field Crops Research*, 183, 56–68. https://doi.org/10.1016/j.fcr.2015.07.012

Nyborg, K., Anderies, J. M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., Adger, W. N., Arrow, K. J., Barrett, S., Carpenter, S., Chapin, F. S., Crépin, A.-S., Daily, G., Ehrlich, P., Folke, C., Jager, W., Kautsky, N., Levin, S. A., Madsen, O. J., … de Zeeuw, A. (2016). Social norms as solutions. *Science*, 354(6308), 42–43. https://doi.org/10.1126/science.aaf8317

Oberč, B. P., & Arroyo Schnell, A. (2020). *Approaches to Sustainable Agriculture*. IUCN. https://doi.org/10.2305/IUCN.CH.2020.07.en

Olsson, P., & Galaz, V. (2012). Social-Ecological Innovation and Transformation. In A. Nicholls & A. Murdock (Eds.), *Social Innovation: Blurring Boundaries to Reconfigure Markets* (pp. 223–247). Palgrave Macmillan UK. https://doi.org/10.1057/9780230367098_10

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S. S. P., Lenferna, A., Morán, N., van Vuuren, D. P., & Schellnhuber, H. J. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences*, 117(5), 2354–2365. https://doi.org/10.1073/pnas.1900577117

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change*, 19(3), 354–365. https://doi.org/10.1016/j.gloenvcha.2009.06.001

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., & Grace, P. (2014). Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment*, 187, 87–105. https://doi.org/10.1016/j.agee.2013.10.010

Peres, R., Muller, E., & Mahajan, V. (2010). Innovation diffusion and new product growth models: A critical review and research directions. *International Journal of Research in Marketing*, 27(2), 91–106. https://doi.org/10.1016/j.ijresmar.2009.12.012

Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., van Groenigen, K. J., Lee, J., van Gestel, N., Six, J., Venterea, R. T., & van Kessel, C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, 183, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020

Porwollik, V., Rolinski, S., Heinke, J., von Bloh, W., Schaphoff, S., & Müller, C. (2021). The role of cover crops for cropland soil carbon, nitrogen leaching, and agricultural yields – A global simulation study with LPJmL (V. 5.0-tillage-cc). *Biogeosciences Discussions*, 1–24. https://doi.org/10.5194/bg-2021-215

Pretty, J. N., Noble, A. D., Bossio, D., Dixon, J., Hine, R. E., Penning de Vries, F. W. T., & Morison, J. I. L. (2006). Resource-conserving agriculture increases yields in developing countries. *Environmental Science & Technology*, 40(4), 1114–1119. https://doi.org/10.1021/es051670d

Reed, M. S., Evely, A. C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., & Stringer, L. C. (2010). What is social learning? *Ecology and Society*, 15(4). https://www.jstor.org/stable/26268235

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461(7263), Article 7263. https://doi.org/10.1038/461472a

Rogers, E. M. (1962). *Diffusion of Innovations, 5th Edition (2003).* Simon and Schuster. https://www.simonandschuster.com/books/Diffusion-of-Innovations-5th-Edition/Everett-M-Rogers/9780743258234

Savory Institute. (2022). Savory Institute - Support Holistic Management & Regenerative Agriculture. https://savory.global/

Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., Gerten, D., Heinke, J., Jägermeyr, J., Knauer, J., Langerwisch, F., Lucht, W., Müller, C., Rolinski, S., & Waha, K. (2018). LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. *Geoscientific Model Development*, 11(4), 1343–1375. https://doi.org/10.5194/gmd-11-1343-2018

Schneider, F., Fry, P., Ledermann, T., & Rist, S. (2009). Social learning processes in Swiss soil protection—The 'From Farmer—To Farmer' project. *Human Ecology*, 37(4), 475–489. https://doi.org/10.1007/s10745-009-9262-1

Smith, T., Benson, S., Ewer, T., Lanel, V., Petykowski, E., Lenton, T., Powell, T., & Abrams, J. (2021). Accelerating the 10 critical transitions: Positive tipping points for food and land use systems transformation. The Food and Land Use Coalition. https://www.foodandlandusecoalition.org/accelerating-the-10-critical-transitions-positive-tipping-points-for-food-and-land-use-systems-transformation/

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., ... Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, 562(7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. https://doi.org/10.1126/science.1259855

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A. B., Courcelles, V. de R. de, Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu, C., Jastrow, J. D., Lal, R., ... Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001

Tosey, P., Visser, M., & Saunders, M. N. (2012). The origins and conceptualizations of 'triple-loop' learning: A critical review. *Management Learning*, 43(3), 291–307. https://doi.org/10.1177/1350507611426239

Tsvetkova, M., & Macy, M. W. (2014). The social contagion of generosity. *PLOS ONE*, 9(2), e87275. https://doi.org/10.1371/journal.pone.0087275

von Bloh, W., Schaphoff, S., Müller, C., Rolinski, S., Waha, K., & Zaehle, S. (2018). Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geoscientific Model Development*, 11(7), 2789–2812. https://doi.org/10.5194/gmd-11-2789-2018

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2). https://www.jstor.org/stable/26267673

Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment*, 3, 380–392. https://doi.org/10.1038/s43017-022-00287-8

Wenger, E. (1998). *Communities of Practice: Learning, Meaning, and Identity* (pp. xv, 318). Cambridge University Press. https://doi.org/10.1017/CBO9780511803932

Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science*, 341(6145), 508–513. https://doi.org/10.1126/science.1239402

Winkelmann, R., Donges, J. F., Smith, E. K., Milkoreit, M., Eder, C., Heitzig, J., Katsanidou, A., Wiedermann, M., Wunderling, N., & Lenton, T. M. (2022). Social tipping processes towards climate action: A conceptual framework. *Ecological Economics*, 192, 107242. https://doi.org/10.1016/j.ecolecon.2021.107242

Earth4All is an international initiative to accelerate the systems changes we need for an equitable future on a finite planet. Combining the best available science with new economic thinking, Earth4All was designed to identify the transformations we need to create prosperity for all. Earth4All was initiated by The Club of Rome, the Potsdam Institute for Climate Impact Research, the Stockholm Resilience Centre and the Norwegian Business School. It builds on the legacies of *The Limits to Growth* and the planetary boundaries frameworks.

www.earth4all.life