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Tailored pathways toward revived farmland biodiversity can inspire agroecological action and policy to transform agriculture

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Advances in agrochemistry in the 19th century, along with increased specialisation and intensification of food production, transformed agriculture triggering a farmland biodiversity crisis. Present economic incentives reinforce this crisis to an unprecedented scale. As the loss of farmland biodiversity undermines the basis of agroecosystems' productivity and, hence, the sustainability of food systems, another transformation is urgently needed. Here, we advocate a concept of future pathways tailored to the characteristics of agricultural land systems and relate these to targeted farming approaches using agroecological principles. The concept depicts a transformative vision to effectively re-establish farmland biodiversity, a cornerstone of sustainable agriculture. It has the potential to support a systematic refinement of existing biodiversity and agricultural policies to enhance their impact and benefit for people and nature.

Biodiversity in the spotlight of agriculture. In the 19th century, Justus von Liebig's innovation in agrochemistry advocated the development of inorganic fertilisers which profoundly transformed agricultural production and constituted one of the key elements of the so-called 'Green revolution' of the 1960s and1970s. The dominant economic growth paradigm that had gained traction at that time spurred exponentially increasing investments in productivity gains and trade liberalisation but disregarded adverse social-ecological consequences[1]. Reliably overcoming limitations in plant nutrition together with improving the chemical control of crop pests and plant breeding set the foundation of agricultural intensification and expansion. The resulting production increase has reduced the prices and hence accessibility of staple food, helping to feed a growing population[1]. Featuring unsustainable forms of agriculture, current economic incentives continue to drive undamped food production at ever lower costs while externalising the environmental effects of food production[1,2]. The primary focus on yield has reduced crop diversity to a few high-yielding crop varieties, short crop rotations, and homogenised agricultural landscapes. This has considerably diminished biodiversity, associated ecosystem services, and nature's contributions to people[2], e.g., pollination by wild animals, nutrient cycling in soil, and pest control[3] rendering the global food system the principal driver of biodiversity loss[2,4]. However, the supporting and regulating ecosystem services generated by the diversity of species residing in and around agricultural land—called farmland biodiversity[5]—are pivotal to agricultural production[2]. Hence, the question arises: which targeted actions can we swiftly implement to enhance farmland biodiversity while ensuring adequate agricultural production?

Farmland biodiversity depends on both the composition and configuration of agricultural landscapes and the intensity of food production[6]. It is hence a central component of land systems and food systems. Interactions between these systems through land use, including food

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systems' impacts on land use change and interdependencies between production, biodiversity, livelihood security, and other sustainability challenges, lie at the core of land system science[7]. In particular, agricultural land systems offer promising opportunities to understand and manage the multiple ways in which landscape-moderated effects on biodiversity and agricultural production co-evolve. Agricultural land systems comprise crop, livestock, and mixed production systems often in conjunction with natural habitats, forestry, settlements, and other land systems[7], particularly when less intensively managed.

Transforming our global agricultural land and food systems toward agroecological production principles, i.e., fundamentally changing the structure and functioning of agriculture, is a widely acknowledged necessity to solve the farmland biodiversity dilemma[8–10]. Agroecology shifts the focus away from maximised production toward optimised effectiveness of biodiversity enhancement and conservation actions while maintaining productivity, ensuring the affordability of healthy diets, and building resilience[11–13]. As an alternative to unsustainable paths of agriculture, agroecology rests on optimising interlinked ecological, socio-economic, and political processes[14,15]. It provides strong impetus to phase out the use of agrochemicals, re-organise agricultural management, and re-establish landscape structure, all essential elements for achieving the vision of sustainable food and agriculture[16]. However, applying the same agroecological principles everywhere is inappropriate, since interactions between agriculture and farmland biodiversity differ according to the level of agricultural production and pressures imposed on biodiversity.

Here, we conceptualise tailored future pathways along which agricultural land systems can best contribute to the overarching vision of restoring and maintaining farmland biodiversity. The pathways are based on the current interplay between agricultural production and farmland biodiversity to which we fitted farming approaches based on agroecological principles depicting a transformative vision toward enhanced farmland biodiversity.

Current relationship between agriculture and farmland biodiversity

Evidence-based syntheses[17,18] indicate a non-linear relationship between agricultural production and farmland biodiversity (black solid line in Fig. 1a). Agricultural production (see *x*-axis in Fig. 1a) subsumes land use intensity in terms of external inputs (e.g., agrochemicals, water, fertiliser, labour) and management strategies (e.g., stocking density, tillage regimes). Agricultural production further integrates landscape composition, i.e., share of agricultural land. It represents a gradient of landscape simplification ranging from complex landscapes in which agricultural land is embedded in a (semi-)natural habitat matrix to structurally simple and cleared (i.e., extremely simplified) landscapes with a very low proportion of non-crop habitats. Farmland biodiversity (see y-axis in Fig. 1a) integrates species, functional and structural levels, mainly displayed as abundance–richness metrics. This integrative perspective helps systematise information about agricultural land system dynamics reflecting advances in ecological science, e.g., the importance of land use- and landscape-moderated effectiveness of conservation initiatives on farmland[17,19].

Before the massive intensification and expansion of agriculture started in the 19th century, many agricultural land systems were extensively used maintaining high farmland biodiversity. They resembled the conditions depicted in the upper left-hand part of the declining relationship (Fig. 1a). These systems are still present today. Their complex landscape structure supports species and habitats that often have an inherent biodiversity value, though species and habitat compositions may differ from undisturbed natural land systems. Due to their inherent biodiversity value, such complex agricultural land systems are specified as high nature value (HNV) farmlands in Europe[20] or satoyama landscapes in Japan[21] and may also encompass traditional smallholder systems worldwide.

We acknowledge the fact that abandonment of extensive farming in agriculturally marginal areas can decrease farmland biodiversity[20] (see lower branch of black solid line in upper left-hand corner in Fig. 1a). Active agricultural management is needed to avoid this degrading branch indicated by a functional space termed 'minimum required production' (Fig. 1a). However, abandonment may also slightly improve biodiversity providing a link to natural or rewilded land systems[22] (see dotted branch of black line in upper left-hand corner in Fig. 1a).

Over the past 200 years, intensification for maximising agricultural production came at the expense of farmland biodiversity, shifting agricultural land systems towards the lower right-hand part of the declining relationship (Fig. 1a). Medium to high production levels of those systems are currently maintained through continuous and substantial external inputs of agrochemicals, while regulating (and supporting) ecosystem services are little demanded. Moreover, these agricultural land systems are highly specialised converging around a few often calorie-rich, but nutrient-poor crops fostering malnutrition including obesity and nutrient deficiencies[23].

At least 20% (semi-)natural habitats have been suggested in agricultural land systems as a prerequisite for ensuring farmland biodiversity and related ecosystem services, e.g., nutrient cycling, pollination and pest control[24,25]. Above such a threshold, regional species pools are sufficiently large and habitat patches connected. This facilitates cross-habitat movement of species and spillover of service-providing species from (semi-)natural habitats to adjacent croplands[6]. Spatial arrangements of cropland and (semi-)natural habitats that enhance edge density can particularly promote functional biodiversity and yield-enhancing ecosystem services. Below the threshold, ecosystem services, if not compensated by fertilisers and other agrochemical inputs, may become the scarcest resource, constraining crop productivity independent of other sufficiently available resources[26]. Hence, we define a 'minimum required biodiversity' threshold (see red dotted line in Fig. 1a) highlighting the risk of farmland biodiversity depletion (see part of the black solid line below the red dotted line in Fig. 1a).

Radically degraded habitats that persistently lost key functional groups and propagule sources can resist recovery, e.g., when communities have been shifted from their original into new states and threshold dynamics inhibit the restoration of original states[27–29]. The further species pools and habitat functionality decline below a minimum required threshold, the slower or even less likely the restoration may become and the greater efforts needed. Emphasising the need to maintain restoration potential, we define a 'maximum tolerable production' level (see Fig. 1a) given finite financial resources and institutional capacities.

Yet, collapsing farmland biodiversity can disrupt agricultural production eventually leading to abandonment which shifts agricultural land systems toward the lower left-hand part of the functional space[30] (Fig. 1a). Extreme weather events, such as droughts, often reinforce degradation and disruption such as evidenced in western Africa[31] or during the 1930s 'dust bowl' when a prolonged drought and severe wind erosion greatly damaged exposed agricultural soils in the United States[32].

Tailoring future pathways toward enhanced farmland biodiversity

High production levels still achieved in many agricultural land systems may enthuse farmers, civil society, or policy makers to

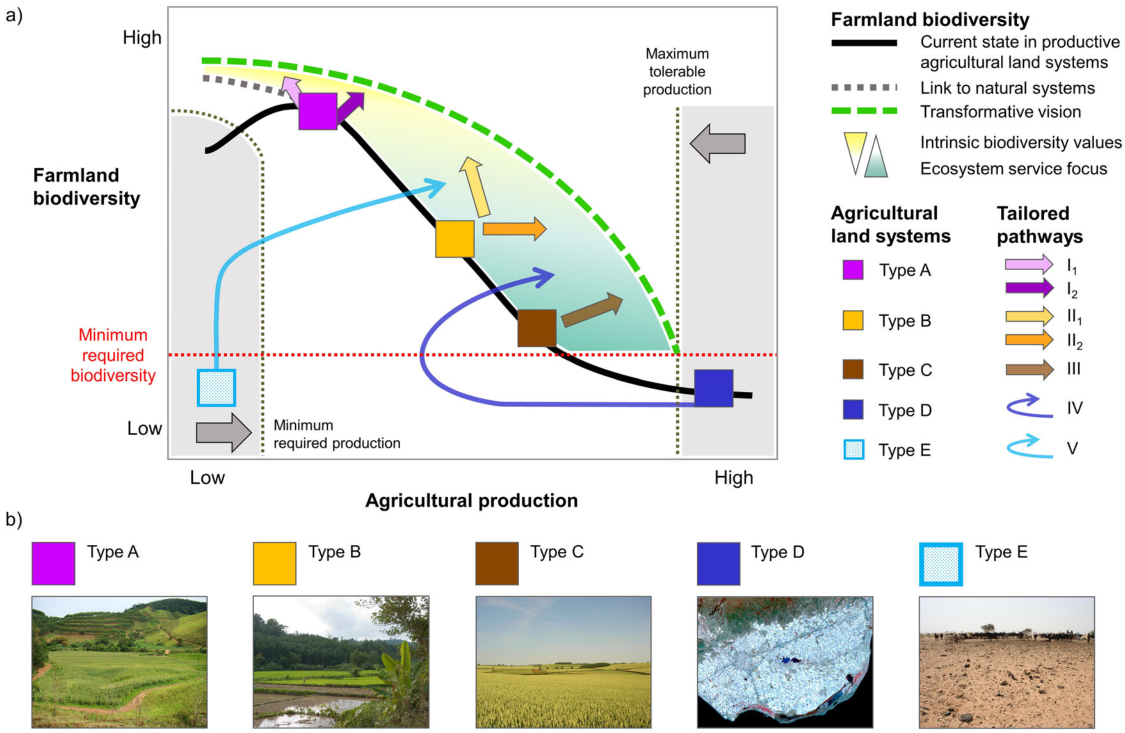

Fig. 1 Conceptualisation of the general relationship between agricultural production and farmland biodiversity together with tailored pathways toward enhanced farmland biodiversity. a Declining non-linear relationship between agricultural production and farmland biodiversity. Pathways I to III are summarised as straight arrows representing overall directions. In contrast, pathway IV involves sequential changes involving de-intensification and restoration action followed by slight re-intensification, while pathway V relies on restoration followed by slight re-intensification. Different lengths of arrows indicate differences in required changes of production and resulting biodiversity improvement. **b** Example photographs of agricultural land system types depict: Type A–Low-intensity livestock system in very diverse mountainous landscape including a protected area in the upper part, southeastern Brazil, Type B–Medium-intensive rice production in diverse landscape with forest remnants, western Philippines, Type C–High-intensity cereal cropping in very simple, homogenised landscape, southern United Kingdom, Type D–Very intensive horticultural production in severely disturbed landscape due to massive greenhouse constructions and agrochemical inputs, southeastern Spain, Type E–Degraded agriculturally marginal land, southern Niger. (**Note a**: Higher agricultural production in Types A–D is represented by solid box fillings differentiating these agricultural land systems from marginal or abandoned agricultural production in Type E indicated by dotted box filling. At medium to high production levels, farmland biodiversity may degrade despite a reduction in agricultural production. Moreover, heavily depleted farmland biodiversity can severely reduce or entirely impede agricultural production. These processes would move agricultural land systems below the current state in productive systems towards the lower left-hand part of the figure. In this paper, we do not consider these trajectories but summarise the consequences of various degradation trajectories in Type E. This type includes degraded agriculturally marginal areas in which smallholders continue to produce food, often locked in low-productivity and poverty traps. It also encompasses systems in which agriculture has been abandoned depicting an extreme consequence of degradation. **Note b**: Photo credits: Type A © Embrapa's multimedia: image repository, by Müller, Marcelo Dias, Embrapa Dairy Cattle Unit, Type B © Vyacheslav Argenberg / http://www.vascoplanet.com, CC BY 4.0, Type C © Jens Dauber, Type D © NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team (margin cropped to resize), Type E © Joris-Jan van den Boom, CC BY 2.0 (margin cropped to resize)).

think that intensive production could possibly continue for some time as these systems seem barely sensitive to degradation. Yet, the picture changes quickly if this way of "high-input, high-output" production is no longer societally desirable. If all production costs were internalised[33], intensive unsustainable production would likely become very expensive and lose people's enthusiasm or acceptance in many places. As a way forward, agroecology[11,13] provides a comprehensive framework to support the tailoring of pathways for agricultural land system transformation. Key agroecological principles encompass diversity, synergies, efficiency, recycling, and resilience, underlining the role of farmland biodiversity, associated ecosystem services, and nature's contributions to people[2] that explicitly recognise a range of worldviews. Highlighting interlinkages between biodiversity, fair trade, consumers, and governance, additional principles emphasise the importance of co-creation and sharing of knowledge, human and social values, culture and food traditions, responsible governance as well as circular and solidarity economy[13]. The agroecological principles enable targeted decision-making by policy makers, farmers, and other stakeholders in specific contexts.

Agroecology embraces key principles of other alternative farming approaches, such as HNV farming, organic farming, diversified farming, ecological intensification, and ecological restoration[26,34–37]. These farming approaches converge with agroecology in their emphasise of farmland biodiversity and ecological interactions, yet pay different attention to ecosystem services, social dynamics, knowledge creation, governance, and food sovereignty. Transformative opportunities also emerge from sustainable intensification[38] and advances in digital technologies[39]. These opportunities can materialise if priority is given to sustainability linking these approaches to agroecological principles, e.g., active encouragement of environmental benefits, knowledge co-production, and systems thinking.

Agroecology and other alternative farming approaches that use or can embrace agroecological principles underpin the tailored future pathways to enhance farmland biodiversity in specific

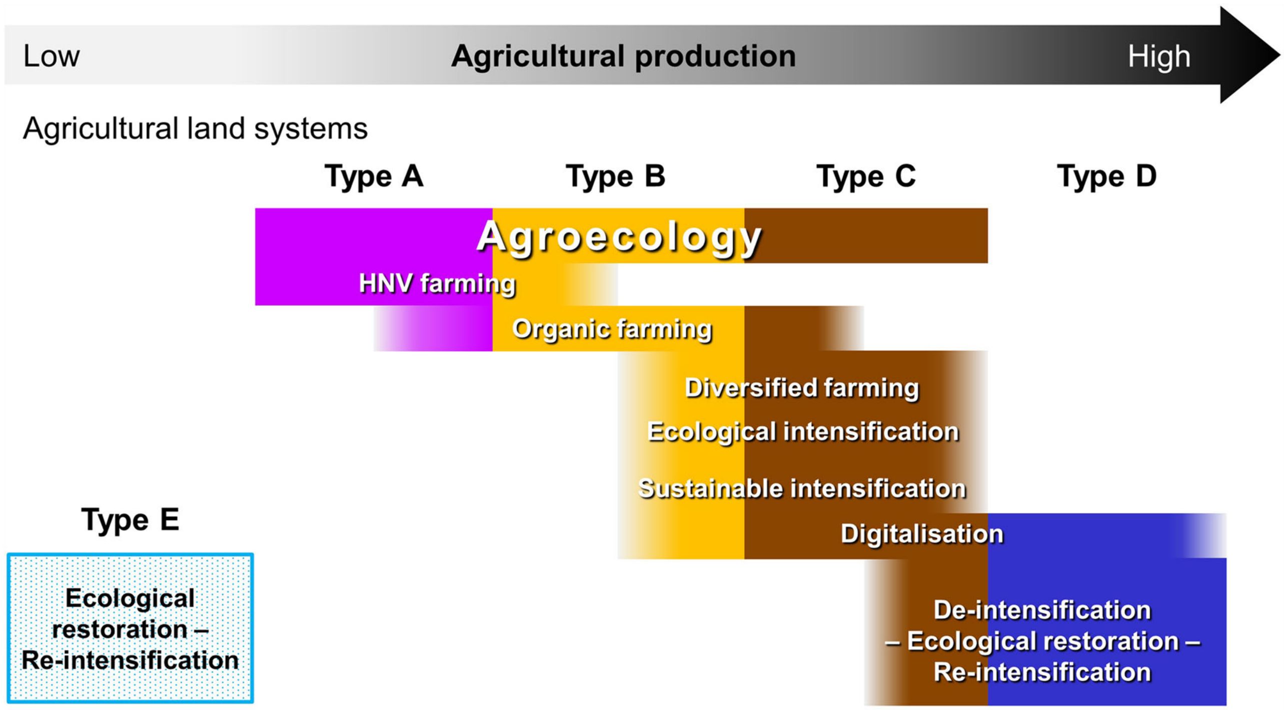

Fig. 2 Agroecology and other alternative farming approaches that share or may emphasise agroecological principles considered most suitable to enhance farmland biodiversity. Approaches are tailored to the characteristics of each type of agricultural land system (A to E, see Fig. 1). Colours refer to the types introduced in Fig. 1. Darker colours indicate better suitability of an approach for the respective agricultural land system. Note that approaches overlap as they share similar principles.

agricultural land system types. To illustrate the conceptualisation of pathways, we locate four different types of agricultural land systems along the declining relationship and one type depicting low agricultural production and farmland biodiversity due to heavy degradation (see coloured boxes in Fig. 1a and examples of agricultural land systems in Fig. 1b). For each type, we consider (a) the current level of agricultural production and state of farmland biodiversity and (b) the underlying cause-effect relations to define tailored pathways (see coloured arrows in Fig. 1a) and suitable farming approaches to enhance farmland biodiversity (Fig. 2). We outline the approaches below in more detail for the selected agricultural land system types highlighting combinations of several approaches that trigger synergistic opportunities.

Type A: Extensive agricultural production and high farmland biodiversity. In extensively used agricultural land systems containing rich (semi-)natural landscape components (see Type A in Fig. 1), agroecology and HNV farming[20] are best suited to conserve and further improve existing habitats and farmland biodiversity (Fig. 2). Currently high farmland biodiversity levels including endemic, threatened and endangered species, still present in Type A systems, may be further increased by slightly de-intensifying production[37] (see light purple pathway I_1 in Fig. 1a). Yet, farmland biodiversity and agricultural production can still simultaneously increase to some extent (see dark purple pathway I_2 in Fig. 1a). For example, agroecological intensification potential has been identified for traditional smallholder systems in the Zona da Mata in Brazil, being part of a global biodiversity hotspot with endemic and threatened fauna and flora[40]. Integration of endemic tree species, use of compost and manure instead of chemical fertilisers and cultivating plants that repel pests to replace pesticides play a key role in conserving threatened species and better connecting forest fragments while enhancing food production. Profound cultural bonds, connection with nature, and engagement with farmers' organisations, non-governmental organisations, and public policies can strongly support agroecological shifts[40]. Public policies, such as those related to solidarity-based economy implemented by the National Secretariat of the Solidarity Economy at the Brazilian Ministry of Labour, improved farmers' access to land and created local markets particularly valuing agroecological products. In Europe, mixed grazing of cattle and sheep, e.g., in the United Kingdom[41], and HNV-specific value chains based on HNV farmland labels marketed at regional scales, e.g., in Ireland[37], have particular potential to simultaneously enhance farmland biodiversity and livestock production.

Type B: Intermediate agricultural production and farmland biodiversity. In agricultural land systems with an intermediate production level (see Type B in Fig. 1), organic farming and agroecology appear most appropriate (Fig. 2). Organic agriculture refrains from the use of synthetic fertilisers and pesticides, focusing on self-regulation, soil fertility, and closed nutrient cycles[42]. It combines traditional conservation-oriented practices with modern farming technologies. Organic farming can benefit farmland biodiversity but mostly leads to lower agricultural productivity, e.g., yields per unit area[25] (see light yellow pathway II_1 in Fig. 1a). However, when enhancing ecosystem services, organic farming and hybrid systems (i.e., integrating mainstream farming and organic practices) have sizable potential for productivity increase and yield stability without sacrificing farmland biodiversity[43] (see dark yellow pathway II_2 in Fig. 1a). For example, pulses and other leguminous cover crops have been shown to fix substantial amounts of nitrogen contributing to biofertilisation of rice in the Philippines[44] and mixed grass-legume pastures enhanced nitrogen fixation and follow-up rice yields in eastern Colombia[45]. Organic production requires considerable manual labour, although often spread more evenly over the growing season. Other challenges relate to controlling weed infestations, accessing funds, and markets for organic foods, storage infrastructure, and distribution facilities[42]. Responding to these challenges, organisation in farmer associations and collective action provide organic smallholder farmers important opportunities to receive the same benefits as large-scale farmers. Use of digital innovations, such as optimising inputs using soil sensors, increasingly available geodata, and robots helping to control weeds, presents other opportunities to overcome the challenges. However, existing challenges still hamper the uptake of organic farming particularly in smallholder systems in low and middle-income countries, such as Iran[46], but also in Europe[47,48].

Although in Europe organically farmed land has steadily increased during the past decades supported by the European Union's Common Agricultural Policy, it does not unfold its full potential. European organic farms include large enterprises, e.g., farms operating on more than 100 ha constitute 52% of organic farmland often associated with monocultural cropping, high levels of mechanisation and specialisation on premium priced crops rather than mixed farming[49]. These characteristics favour simplified landscapes with limited farmland biodiversity. Having emerged as an increasingly attractive sector for large capital investment, organic farmland allows investors to increase profitability and to justify its legitimacy particularly in times of crises[49]. This clearly challenges efforts to transform agricultural land systems toward truly enhanced farmland biodiversity and sustainability.

To leverage the potential of organic farming at higher scales, in Europe and beyond, governments are required to create enabling environments including co-development of context-sensitive options, value chains, and market development[42]. Valuing and supporting those organic farms that implement agroecological principles rather than others that simply replace inputs is essential to use the full social-ecological potential of organic farming. Synergies arise from combining organic farming with diversified farming (e.g., multi-cropping and crop rotations) substantially reducing yield gaps compared with unsustainable ways of production[50]. Certification of organic products yields higher prices presenting an opportunity to compensate higher labour and processing costs, particularly in small and medium sized farms. Low-cost alternative certification methods, such as Participatory Guarantee Systems with large coverage in India, Peru, and Kenya and increasing implementation at global scale, are particularly important for smallholder farmers[51].

At intermediate production levels, agroecological intensification provides further opportunities to increase crop productivity while reducing pesticide application, benefitting from an agricultural sector's redesign and knowledge generation in farmers' grassroots movements (see dark yellow pathway II_2 in Fig. 1a). It aims at improving diversification, resource use efficiency and responsibility, among other agroecological principles. For example, farmers in Cuba reduced pesticide application by 15% and enhanced crop productivity by 150% using e.g., organic soil amendments and diversification at farm level[52]. Moreover, spatio-temporal rearrangement was a prerequisite for encouraging the maintenance or regeneration of (semi-)natural habitats serving as propagule sources of natural pest and disease enemies. This agroecological intensification involved a nationwide redesign of land tenure, social organisation of production, educational programmes and financial structures of the Cuban agricultural sector. The redesign was important as Cuban agriculture until the 1980s was rooted in the 'Green revolution' strongly relying on fertiliser and pesticide imports but became dysfunctional in the 1990s with the collapse of the socialist community of states and the United States' trade embargo[52].

Type C: More intensive agricultural production and low farmland biodiversity. In more intensively used agricultural land systems with simplified landscapes (see Type C in Fig. 1), agroecology, diversified farming, and ecological intensification (Fig. 2) are considered best suited to enhance both farmland biodiversity and agricultural productivity (see pathway III in Fig. 1a). For example, agroecological crop management including non-chemical approaches to control pests and diseases tended to increase crop productivity particularly in mixed crop-livestock systems in France[53]. Redesigning agricultural land systems so that they take advantage of complex interactions and synergies between crop and non-cop biodiversity and supporting farmers to adapt their practices is essential to initiate transformative change resting on biological pest and disease control. Increased spatio-temporal diversity of cultivated crop species and varieties, a key principle of diversified farming[35], also simultaneously improved crop production and farmland biodiversity in worldwide field experiments[54]. Shifting the focus, ecological intensification emphasises the management of service-providing species and enhancement of ecosystem functions to regulate and support agricultural production[26,36]. For example, wildlife habitats at field edges and in discrete patches, including native wildflowers and grasses, provided foraging, nesting, and refuge habitat for pollinators and natural enemies of crop pests enhancing crop yields in the United Kingdom[55]. Crop diversification can synergistically support ecological intensification reducing pest infestation and the need to apply insecticides while increasing crop yield and economic return[56]. Agroforestry also simultaneously increases multiple ecosystem services, e.g., pest and disease regulation, soil water infiltration, and soil productivity[54].

Progress in more intensively used agricultural land systems (see Type C in Fig. 1) can thoughtfully be supported by sustainable intensification[38] (Fig. 2). Yet, it needs to go beyond incremental modifications systematically fostering agroecological principles, e.g., working with ecological processes, strengthening farmers livelihoods and promoting equity[57]. Digitalisation (Fig. 2) presents another opportunity to increase both agricultural production and farmland biodiversity[39,58] (see pathway III in Fig. 1a) when integrated with agroecological principles, e.g., democratic knowledge, governance, and transfer approaches[13]. Due to high costs associated with digital farming, its adoption is most suited for larger farms or production of premium priced products (e.g., horticultural crops). Shared and inclusive digital infrastructure and services are a promising way forward to facilitate adoption in smaller farms[59].

Type D: Extremely intensive agricultural production and depleted farmland biodiversity. Extremely high production extracted from agricultural land systems with strongly simplified or even cleared landscapes in which key ecological functions have vanished (see Type D in Fig. 1) demand a path of de-intensification, ecological restoration[34], and re-intensification (see Fig. 2 and dark blue curved pathway IV in Fig. 1a). Empirical evidence is insufficient to judge to what extent farmland biodiversity in such intensively used systems has already diminished below the minimum required biodiversity threshold. Yet, the very intensive horticultural production in southeastern Spain associated with massive greenhouse constructions and agrochemical inputs[60] possibly includes Type D agricultural land systems (Fig. 1). In such systems, almost no semi-natural habitat is left and species pools are too depleted to respond to any agri-environmental management[19]. To allow ecological functions to recover, production needs to be actively reduced first (see horizontal part of pathway IV in Fig. 1a). Then, ecological restoration can revitalise severely degraded agroecosystems and habitats by active intervention[34] shifting an agricultural land system over the minimum required biodiversity threshold (see upward leading part of pathway IV in Fig. 1a).

Rebuilding healthy soils and semi-natural habitats are key restoration approaches practiced in southeastern Spain[61]. For example, soil solarisation and biofumigation, supported by increase of soil organic matter content, contributed to restore soil biodiversity and associated ecosystem services, e.g., nutrient cycling and agrochemical pollutant removal. Native plant species used to restore semi-natural habitats in between greenhouses provided food and refuge for natural enemies of crop pests, such as spiders and other predators supressing thrips and whiteflies in greenhouses. In these examples, on-farm experiments, demonstrations, and workshops were essential to the co-creation of knowledge and sharing of experiences among farmers[61]. The redesign based on ecological processes rested upon farmers' reconnection with nature including recognition of ecosystem services as an integral part of their farming activity, regulations that obliged hedgerow establishment, and incentives by regional administration to subsidise green infrastructures. Close collaboration with business, research, and market institutions and knowledge exchange among the multiple actors were essential in creating synergies and navigating transitions to scale up niche innovations[61]. Future research is needed to determine the species that best control crop pests, their minimum viable population sizes, and minimum area required to accommodate viable species populations[62,63]. Once the minimum biodiversity level is re-established, if possible at all, and ecosystem services reliably support agricultural production, production can be agroecologically re-intensified (see upper rightward pointing part of pathway IV in Fig. 1a).

Type E: Marginal or abandoned agricultural production and depleted farmland biodiversity. Heavily degraded land on which agricultural production has severely declined or been abandoned (see Type E in Fig. 1) requires systematic ecological restoration[34] before agricultural production can be carefully re-intensified (see Fig. 2 and light blue curved pathway V in Fig. 1a). Agroforestry prominently illustrates this pathway along which millions of hectares of barren land were transformed to biodiverse, productive systems. An agroforestry method called 'farmer-managed natural regeneration' enabled farmers in Niger to restore farmland biodiversity and ecosystem services, e.g., providing habitats for predators of agricultural pests, improving soil fertility by use of nitrogen-fixing leguminous trees, and enhancing nutrient cycling[31] (see vertical part of pathway V in Fig. 1a). To establish these agroforests, farmers systematically selected, pruned and protected stems that sprouted from remaining stumps of native tree species and regenerated natural seedlings. Managing existing native vegetation was key to effective restoration as it grows rapidly, makes farmers independent of external projects, is valued in the local economy, and has multiple uses (e.g., food, fodder, firewood, mulch). Trees were intercropped with traditional food and cash crops, such as millet, sorghum, peanuts, hibiscus, and sesame, showing increased yields in sufficiently matured systems (see upper rightward pointing part of pathway V in Fig. 1a). Crop yields benefitted from nutrients that dropping leaves and fruits transferred from trees to crops and manure input from browsing and sheltering livestock. Surpluses were sold at local markets. In these biologically active agroforestry systems, food security, drought resilience, and local incomes substantially improved[31].

Overall, farmer-managed natural regeneration enabled cheaper, sustained, and better replicable restoration than earlier attempts that had focused on technical and costly solutions related to tree nurseries, planting, and weeding but could not even sustain 20% of the trees planted[31]. New inclusive governance structures that operated across local and national levels and involved all stakeholders in decision-making (e.g., planning activities, supervising on-going work, monitoring crop experiments) played a central role in this transformative pathway[31,64]. Similar experiences of mutually supportive biodiversity restoration and sustainable re-intensification on severely degraded land were reported from other regions, e.g., northern Ghana[65] and northeastern Brazil[66]. In the United States, effective policy and long-term commitment are urgently needed to restore biodiversity, soil carbon sequestration, and other ecosystem services in severely degraded, abandoned croplands in the Great Plains[67].

Differentiated perspective on farmland biodiversity. The above discussion of tailored future pathways illustrates a broad distinction between conserving intrinsic biodiversity values and the enhancement of supporting and regulating ecosystem services associated with farmland biodiversity[17,68] (see yellow and turquoise shaded areas in Fig. 1a). Conservation of intrinsic biodiversity values plays a key role in heterogenous and extensively used agricultural land systems as these have become vital substitutes for natural habitats and hence for the survival of many species. It focusses on protecting for example rare and endangered species or high biodiversity value habitats where they still exist. Maintaining species and habitat diversity is essential for ensuring resilience to climate and other environmental disturbances[69]. Yet, not all species contribute equally to the delivery of ecosystem services, such as only a few common pollinators provide most pollination services[68], demanding a differentiated perspective. In contrast to intrinsic biodiversity values, enhancing functional biodiversity targets ecosystem services, such as crop pollination, pest control, nutrient cycling in soil, and water regulation. Actions to enhance functional biodiversity are best suited in simplified and intensively managed agricultural land systems with strongly reduced ecosystem services. In particular, they support the replacement of heavily used external inputs helping to safeguard food production while minimising environmental harm[26]. Hence, the distinction between conserving intrinsic biodiversity values and enhancing ecosystem services not only promotes the design of more effective agri-environmental policy measures but also the transformation of agricultural production.

The tailored pathways lead to specific areas in the target space which is differentiated by a gradient ranging from a focus on intrinsic biodiversity values to ecosystem services (Fig. 1a). In reality, the linear pathways I to III (Fig. 1a) may take various forms such as those illustrated by empirically found exponential relationships depending on diversity measures (e.g., species richness or abundance) and functional species groups[70]. Pathways IV and V (Fig. 1a) involve sequential changes including threshold dynamics and step-changes[27–29]. The tailored pathways indicate potential biodiversity levels attainable for each agricultural land system type depicting an overarching future vision.

Transformative vision

The tailored future pathways (Fig. 1a and previous section) provide seminal avenues based on selected and prioritised farming approaches focussing on agroecological principles (Fig. 2). The combined pathways establish a vision essentially transforming the sharply declining current relationship into a concave relationship between agricultural production and farmland biodiversity (see green dashed line in Fig. 1a). The functional space in between the current state of productive agricultural land systems and the transformative vision, bounded by the minimum required biodiversity threshold, defines the target space for transformational change. Reaching the target space requires a systematic re-organisation, i.e., transformation of agricultural land systems based on agroecological principles to effectively restore and maintain farmland biodiversity while ensuring productive and socio-culturally valued agroecosystems. Depending on the current degradation level, each type of agricultural land system contributes specific opportunities for realising the vision, expressed as potential biodiversity levels that may be reached when following the tailored pathways. In contrast to confined agroecological states to which natural, traditional and industrial agroecosystems may evolve[71], the transformative vision presented here captures the reconfigured relationship along the entire production and farmland biodiversity gradients.

Critical to realising the vision will be a reconfiguration of the principles of agriculture[8] and an application of those principles on all agricultural land. This goes far beyond the current state in which alternative approaches are often applied in niches. For example, organic farming has been promoted and realises special prices but still remains practiced on only 2% of the global agricultural land with largest area shares in Australia, Europe, and Latin America[51].

Our transformative vision highlights the potential of shared land in which biodiversity and agriculture thoughtfully interact. At global scale, we cannot afford to give up or lose valuable farmland including those heavily degraded or abandoned areas included in Type E (see Fig. 1) and try to compensate agricultural production elsewhere, e.g., in Europe. Future climate change may substantially alter land suitability for agricultural production so that currently productive areas may fail to produce enough food and fodder, severely increasing risks of food supply instability[72]. This strongly confines ideas to neglect the ecological restoration of currently abandoned, degraded land. From an agroecological perspective, using all productive and restorable land worldwide is fundamental. It promotes locally adapted agriculture and supports economic independence and equitable food systems in which stakeholders choose what crops, livestock, and trees they produce, how and where, and what they eat[12]. Land sharing becomes even more important as the most productive, industrialised systems in the world, e.g., located in the United States and western Europe, only contribute 13% of the global cereal production[73]. These systems could best contribute to global food security by reducing their enormous impact on farmland biodiversity and the environment and replacing fossil fuel-based inputs while keeping current productivity[73].

Contrasting the segregative reasoning of protecting biodiversity primarily in conservation areas (e.g., http://www.halfearthproject.org), we show that the conservation of intrinsic biodiversity values also has a role to play on agricultural land (see Types A and B in Fig. 1). This contrasts approaches that encourage abandonment and regeneration of agricultural land that is currently least agro-environmentally efficient[74]. Our vision fully incorporates the substantial benefits that farmland biodiversity and the associated supporting and regulating ecosystem services deliver for increased, socio-culturally valued, and resilient agricultural production and for greater independence of fossil fuel-based inputs[26]. Hence, it presents a sound alternative to the idea of converting small remaining fragments of semi-natural habitats that would not substantially increase agricultural production but reduce species richness[75]. This is a major shift in the debate around food security in which increased production is often proposed as the main strategy to feed the growing world population[76]. This productionist focus assumes that intensification and higher resource use efficiency can increase yields around the world, yet neglecting biodiversity benefits to improve efficiencies and overcome evident yield plateaus[77].

Lessons and the way forward

Despite the striking biodiversity crisis, a holistic agenda on sustainable agriculture and food systems is only starting to emerge[13]. The tailored pathways presented here highlight that targeted farming approaches incorporating agroecological principles are needed and readily available to realising the transformative vision of enhancing farmland biodiversity while safeguarding food production. Yet, they demand differentiated incentives adapted to diverse agricultural land system types.

Our concept helps to evaluate if and under which conditions existing biodiversity and agricultural policies[78–80] provide effective incentives to sustainably transform agricultural land systems. To provide recommendations for decision-makers on how to best achieve the transformative vision, the likely action space and effectiveness of existing biodiversity and agricultural policies can be evaluated within the target space for transformational change. This requires a discussion of how well the policies resonate with the tailored pathways and apply the necessary integrative thinking to effectively address important opportunities.

Promising solutions can best be developed and tested in stakeholder-centred initiatives such as on-farm experimentation or living laboratories at landscape scale experimenting on real farms with farmers and other food system actors[81]. Our conceptual framework allows to integrate other farming approaches that apply agroecological principles, such as nature-inclusive agriculture[82] and permaculture[83]. Archetype analysis[84–86] can reveal recurrent, i.e., archetypical patterns in the interactions between agriculture and farmland biodiversity as well as transformative potential[87], helping to generalise and up-scale knowledge and response options in context-sensitive ways. For example, natural pest control archetypes demonstrate how knowledge about the biological regulation of crop pests can be synthesised and recurrent patterns identified across agricultural land systems and regions[88]. Integration of agroecological principles in archetype modelling will further increase its predictive power and strengthen up-scaling lessons.

To fully tap existing potential and enhance multiple farmland biodiversity aspects, synergies need to be catalysed, systems thinking applied and multiple leverage points addressed. This needs to be embedded in a reform of the global food system and economic incentives[89], e.g., by designing and implementing payment schemes for ecosystem services[90] and by internalising the costs of re-establishing farmland biodiversity and ensuring healthy nutrition. These are essential steps to replace the ever-increasing production and cheapening of food with an environmentally-friendly and nutritious food paradigm in order to leave the current devastating trail of agricultural food production and enter a sustainable path.

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D.S. designed the research, synthesised the literature, and wrote the paper. S.K. contributed to the design, synthesis of literature, discussion, and writing of the paper. J.D. contributed to the design, discussion, and writing of the paper.

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