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Agricultural ecosystems and their services: the vanguard of sustainability?

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Sustainable Development Goals offer an opportunity to improve human well-being while conserving natural resources. Ecosystem services highlight human well-being benefits ecosystems, including agricultural ecosystems, provides. Whereas agricultural systems produce the majority of our food, they drive significant environmental degradation. This tension between development and environmental conservation objectives is not an immutable outcome as agricultural systems are simultaneously dependents, and providers of ecosystem services. Recognizing this duality allows integration of environmental and development objectives and leverages agricultural ecosystem services for achieving sustainability targets. We propose a framework to operationalize ecosystem services and resilience-based interventions in agricultural landscapes and call for renewed efforts to apply resilience-based approaches to landscape management challenges and for refocusing ecosystem service research on human well-being outcomes.

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Introduction

Covering 38% of the terrestrial, ice-free surface of the planet, agricultural ecosystems are the largest ecosystems of the Anthropocene, and are a major contributor to the breaching of multiple planetary boundaries [1•,2••]. Agriculture contributes to between 19 and 29% of total global GHG emissions [3], 69% of anthropogenic freshwater consumption [4••], and 31% of wild biodiversity loss [5,6]. It is also the primary driver for the disruption of phosphorus, and nitrogen cycles [7]. Because agricultural systems are the principal interface between human and environmental interactions [8•], they are arguably our single most important solution space for addressing both environmental sustainability and food security challenges as articulated in the Sustainable Development Goals (SDGs). An ecosystem service-based approach guides this transition towards and agriculture that contributes to sustainability by emphasizing the multifunctional contributions that agriculture can make to multiple dimensions of human well-being [9]. Furthermore, the self-organizing nature of ecosystem services embeds resilience attributes into intervention actions. Novel approaches that secure the natural resource base and the ecosystem services upon which agriculture is founded can relieve these pressures by leveraging agriculture's contribution to multiple global demands including food and nutrition security [4••].

Contributions to sustainable development

Two of the important distinctions of the SDGs from the MDGs include the global nature of the compact—addressing changes that need to be taken by developed as a well as developing countries, and the greater attention given to interactions between goals. This interdisciplinary focus has generated numerous reviews articulating the contributions of various disciplines to the SDGs such as from environmental sciences [10] and nutrition [11]. What is evident from these analyses, and particularly from the environmental sciences, is that there exists an organizational hierarchy to these goals with the environmental goals serving as both the foundation of their attainment, and the broader context for their achievement. This is also evident in the planetary boundaries [1•,12] and their modification by Raworth [13] into a "planetary donut" which depicts environmental boundaries as limits to be maintained (outer circle), and social foundations to be raised (inner circle) to secure a "safe and just" operating space for humanity. Ecosystem services bridge these two domains by providing a means of managing environmental processes for human well-being and emphasizes environmental goals as a means to sustainably attaining social goals. This framework needs to go hand-in-hand with innovations in socio-economic thinking and approaches to ensure policies and institutions are in place to enable the new paradigm of development.

Ecosystem services in agriculture

An ecosystem approach, as defined by the Convention on Biological Diversity and utilized in conservation biology, favors the integrated management of land, water and living resources to promote conservation and sustainable use in an equitable way. This is complemented by ecosystem services broadly defined as nature's benefits to people [14]. As such, ecosystem service management interventions must thus be able to demonstrate causal relationship between change in an ecosystem attribute and a resultant measure of human or societal well-being [8•]. While forests and other natural ecosystems remain important sources of ecosystem services, the central role of agricultural ecosystems in determining human well-being merits much greater recognition [15•,16]. Relatively small changes in agricultural management practices can tip the balance securing both the food production, and ecosystem service production functions of agriculture [17••]. The range of intervention options in natural ecosystems is limited when compared to the long intervention history, and myriad of management practices available for agricultural systems. This makes agricultural ecosystems a more malleable solution space to implement novel management practices and to deploy new technologies for improving ecosystem services such as soil carbon sequestration, improved water quality (SDG6), and habitat for biodiversity (SDG 14 & 15). Fundamental advancements in agroecology and agroforestry in combination with redesigned high tech systems such as precision agriculture, remote sensing and soil probiotics are offering innovative options for ecosystem service management in agriculture. These can substantially enhance ecosystem service delivery and capture while safe-guarding and securing food production objectives [17••].

All too often poorly managed agricultural systems have unintended consequences that negatively impact the flow and provision of ecosystem services to or from agricultural lands caused by nutrient runoff, pesticide poisoning and habitat loss and degradation [18]. Existing and novel agricultural management practices can enhance the provision of numerous ecosystem services while reducing agriculture's negative externalities [18,19,20••]. This includes services central to food production (SDG 2) comprising pollination, pest control and soil nutrient storage and cycling [15•]. It also includes services obtained from agriculture such as nutritious food (SDG 3), fuel (SDG 7) and fiber production provisioning and regulating of water flows (SDG 6), carbon sequestration (SDG 13) providing security from natural hazards, climate change mitigation, and cultural services including spiritual and recreational values, and habitat for both wild and functional biodiversity (SDG 14 & 15) [18,20••,21,22,23,24••]. The ecosystem services concept provides a systems-based approach to describe and manage agricultural ecosystems that facilitates a more holistic view [25] and highlights the centrality of agriculture to achieving global sustainability goals, as well as an opportunity for greater convergence between agricultural and nature conservation objectives [26••].

Resilience in agriculture

Resilience thinking recognizes the tightly-coupled relationship between people and environment and describes society as complex socio-ecological systems that are continuously in flux as a result of internal and external influences [27,28]. While many definitions of resilience exist, here we adopt the definition that resilience is the ability of a socio-ecological system to undergo change while maintaining support for human well-being and livelihoods (adapted from [29]). Ecosystem services, because they are founded on the principles of self-organization and regulation of ecological communities, become important contributors to agricultural resilience [e.g., [30]]. Improving the resilience of agricultural systems and landscapes against climatic variability, extreme weather events, pest outbreaks, market volatility, institutional changes or other stressors is critical to the achievement of SDGs. Incorporating resilience thinking into ecosystem service approaches means seeking to identify and manage for change [29] where interactions between ecosystem service supplies or benefits create trade-offs that undermine livelihoods. This may mean prioritizing conservation of ecosystem services that are associated with several livelihood benefits, such as water flow regulation underpinning water supplies, soil nutrient storage and cycling, flood damage mitigation [31] diet diversity [32], or services that act as safety nets in times of stress [33]. It also requires allowing redundancy in ecosystem service suppliers [34] to reduce risk of service loss in the face of change.

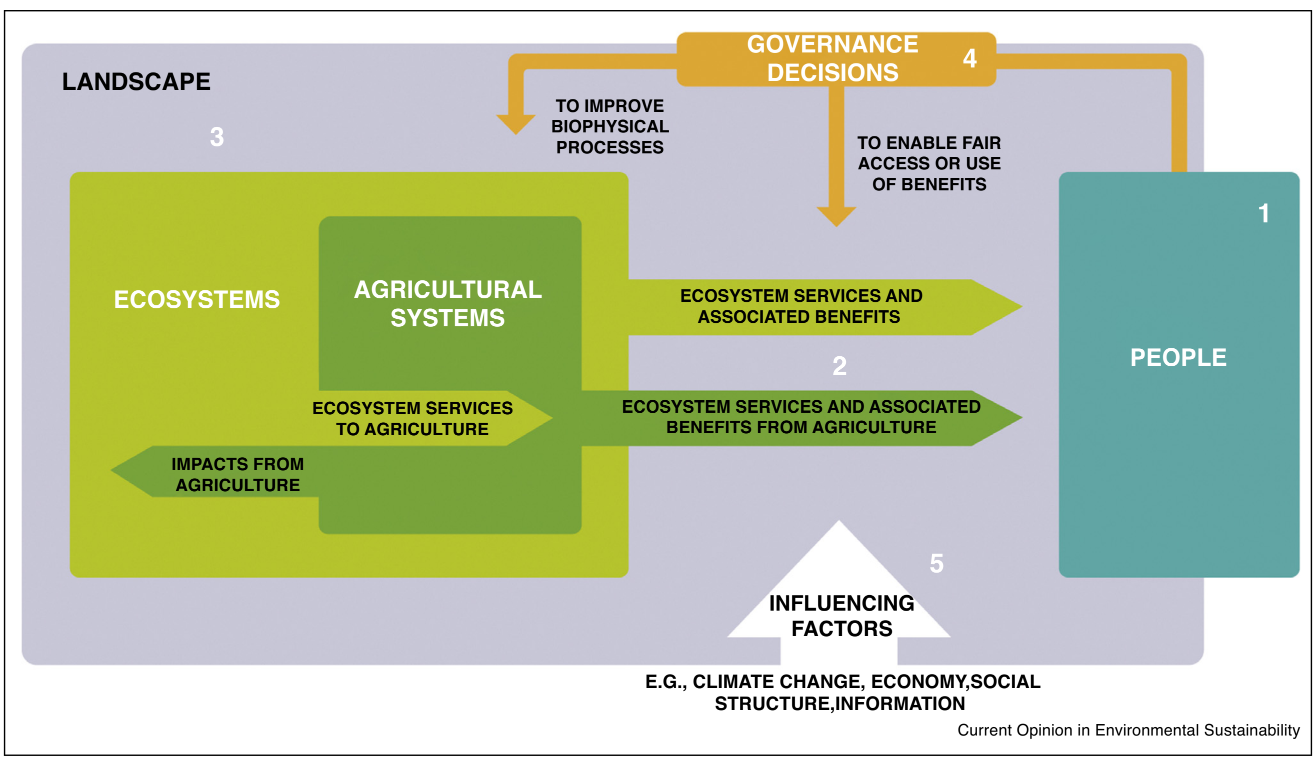
An ecosystem service and resilience framework for agriculture

Moving toward greater inclusion and operationalization of ecosystem service and resilience-based approaches in agricultural development necessitates a re-envisioning of agricultural systems as complex adaptive socio-ecological systems at the vanguard of sustainability challenges [26••,35]. From an operational point of view, transitioning to an ecosystem service and resilience approach requires recognizing several unique features and components of agricultural systems, which we attempt to capture in our Ecosystem Services and Resilience (ESR) framework (Figure 1). First, the framework must clearly articulate the imperative people centered outcomes of an ecosystem service and resilience-based approach. The approach is thus unapologetically anthropocentric, albeit with intergenerational sustainability underpinning the articulation of benefits to people.

Second, the framework recognizes that agricultural management decisions both determine the extent to which agricultural ecosystems are managed for food production, and the impacts of agriculture on the environment. Similarly, these management decisions can determine the extent to which agricultural systems contribute to non-food provisioning ecosystem services, such as carbon sequestration in agricultural soils for climate mitigation [36]. The recently released UNEP TEEB for Agriculture and Food Interim report [15•] captures these well as the invisible or unrecognized positive and negative" flows of ecosystem services from agriculture (Figure 2).

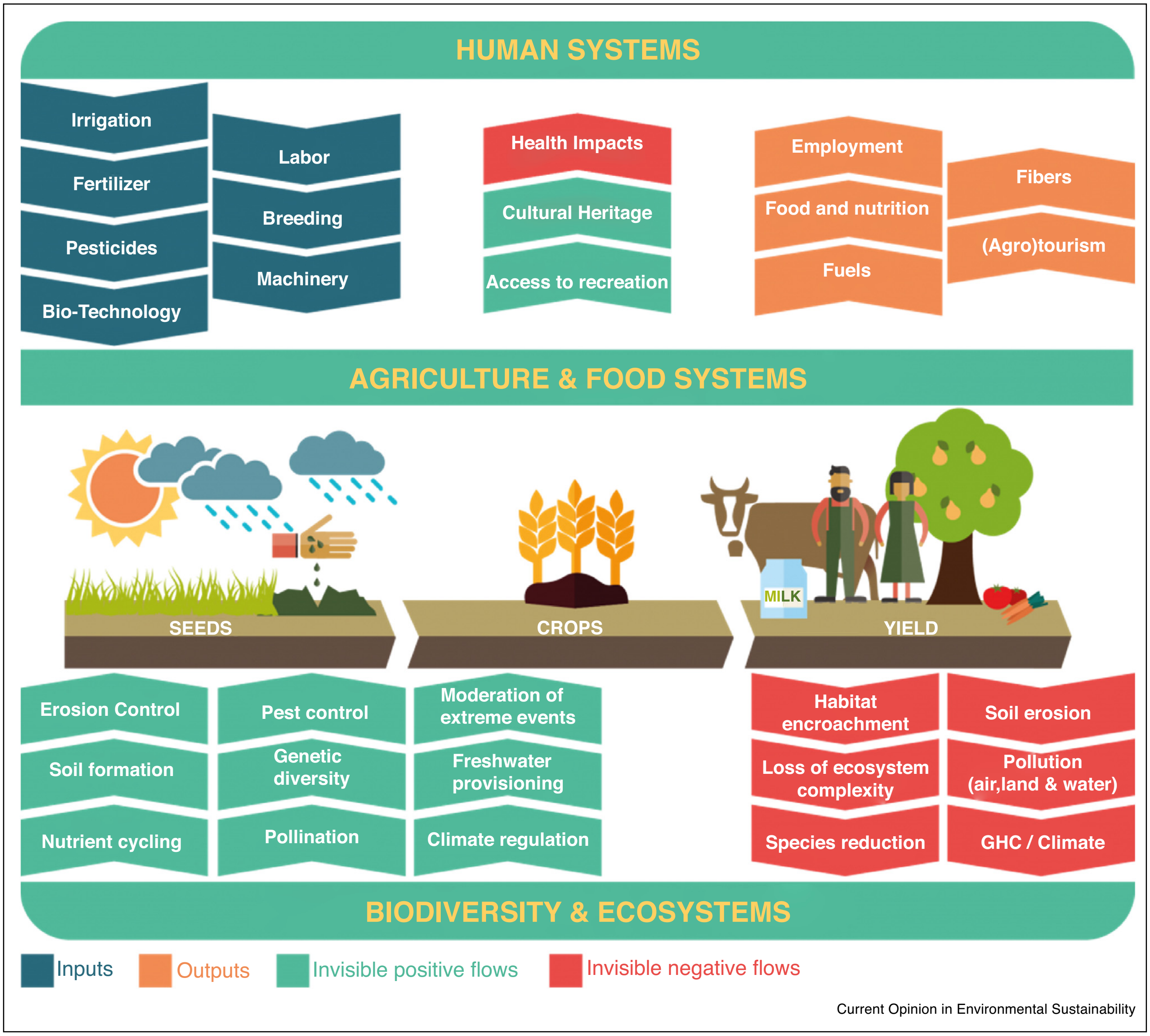
Third, capturing these multiple contributions requires an integrative and systems-based approach. While many methods exist, landscape approaches are currently the most suitable in light of the strong land-based impacts of agriculture. Landscape approaches facilitate the understanding and management of interactions between land use change and multiple stakeholder interests. While

Figure 1



An ecosystems service and resilience (ESR) framework for agricultural landscapes which highlights the need for a better articulation of the impacts and benefits to people (1); the capacity of agricultural management to provide services complementing food production services (2); but necessitating landscape-based approaches to describe and quantify interactions between system components and levels (3); that must be supported with governance decisions that improve the contributions of biophysical processes contributing to service provision, and to enable fair access and use of benefits (4); while facilitating learning and adaptive capacity to external influencing factors, whether social or environmental in their construct (5).

Figure 2



The Economics of Ecosystems and Biodiversity (TEEBAgriFood) framework for capturing the visible and invisible costs and benefits of agricultural and food systems on both ecosystems, and human systems (TEEB [15•]).

landscape approaches do not automatically capture temporal dimensions, there are a growing number of tools available to project the impacts of land use change on ecosystem services provision through both time and space.

Fourth, novel management decisions and governance structures are needed to promote human actions that contribute towards a better provision of ecosystem services in agricultural landscapes, and to enable fair access to and sustainable use of those benefits by beneficiary communities.

Finally, we emphasize the need for agricultural research to adopt an emerging ecosystem-based perspectives and approaches [26••] to recognize agricultural systems as tightly-coupled with natural ecosystems and as complex adaptive socio-ecological systems constantly subject to both environmental and socio-cultural change, to which food provisioning functions must remain resilient [27,37].

This ESR framework is designed to enhance efforts to understand and manage ecosystem services that can build socio-ecological system resilience to stresses and shocks to support food security and poverty alleviation goals as stated in the SDG's. Resilient systems in agricultural landscapes are better able to recover their fundamental structure and functionality in the face of change or to transform into new regimes where this has desirable environmental and social outcomes. Incorporating resilience into an ecosystem service-based approach identifies threats and thresholds affecting ecosystem service provision and reduces these threats while increasing the ecological and human capacity to recover and avoid crossing critical thresholds. This should be carried out within the context of improving development outcomes over long time frames, which means that priority should be given to building resilience in ecosystem services that benefit the poor or disadvantaged.

To facilitate the gradual integration of ecosystem service and resilience perspectives into agriculture, we propose five core principles that serve to guide research and interventions (Box 1). We briefly recognize these as follows:

Core principle 1: meeting the needs of people is fundamental

Decisions regarding the use and management of ecosystem services should positively benefit people, particularly the poor or disadvantaged, by increasing stable access to sustainable diets, or reducing exposure risk to water, air, or vector borne diseases for example. While ecosystem service tools and technologies remain strongly rooted in the environmental sciences with approaches that relate changes in ecosystem structure to changes in service provision and flows, we must improve capacity to demonstrate causality and extent of contribution to improved human well-being [38]. To accomplish this, ecosystem service-based approaches must move beyond biophysical measures of impacts to better demonstrate the impact of ecosystem change on the different dimensions of human well-being. Such an approach emphasizes not only the inherent value of environmental goals (e.g., SDG 14 Life Below Water; SDG 15, Life on Land), but also their actual contribution to social goals (e.g., SDG 1 No Poverty, SDG 2 Zero Hunger, SDG 3 Good Health and Well-Being [39]).

Core principle 2: people use, modify, and care for nature which provides material and immaterial benefits to their livelihoods

People and nature are inextricably linked, tightly-coupled and function within complex adaptive systems. Human actions and natural resources use choices affect the processes that provide ecosystem services, their flow and distribution. The presence, recognition and distribution of ecosystem services and their benefits drive societal choices and can create or reduce livelihood options. These feedbacks and complexities highlight that beneficiaries and providers of ecosystem services are intrinsically linked [40]. Both societal and ecological components of agricultural systems and landscapes, and the interactions between, them must be understood and incorporated into governance decisions. This requires methods of ecosystem service analysis capable of matching ecosystem service providers to beneficiaries, and elucidating effects of management decisions on both ecosystem functions and processes underpinning service provision and on flow to beneficiary groups.

Core principle 3: cross-scale and cross-level interactions of ecosystem services in agricultural landscapes can be managed to positively impact development outcomes

Ecological and societal structures and functions influencing the provision of ecosystem services operate across a wide range of spatial, temporal, ecological and jurisdictional scales, each of which can be distinguished into several levels [30]. Correctly identifying the ecological (genetic, population, community, ecosystem), spatial (hectares, square kilometers, regions), and temporal (months, years, decades) levels at which changes to ecosystem service supplies can occur, and matching these to appropriate jurisdictional levels (political units, such as farm, village or national boundaries) is critical for sound ecosystem service management [41]. However these rarely align, as different ecosystem services tend to manifest or be produced at different levels. For example, increased soil carbon through conservation tillage can enhance farm level soil fertility, reduce watershed level sediment loads, and contribute to global climate mitigation goals. Thus the impact of changes at different levels of an ecosystem need to be monitored at appropriate

Box 1 Five core principles underpinning research and application of ecosystem services in agricultural ecosystems and landscapes.

Principle	Description
People	Meeting the needs of poor people is fundamental.
People and Nature	People use, modify, and care for nature which provides material and immaterial benefits to their livelihoods.
Scale	Cross-scale and cross-level interactions of ecosystem services in agricultural landscapes can be managed to positively impact development outcomes.
Governance	Governance mechanisms are vital for achieving equitable access to, and provision of, ecosystem services.
Resilience	Building resilience is about enhancing the capacity of communities to sustainably develop in an uncertain world.

points in space and time to the decision making need [41]. Embracing a cross-scale and cross-level approach provides an opportunity for nested management, where ecosystem service management at one level can be integrated with management at coarser levels in ways that might not be identifiable without cross-level analysis.

Core principle 4: governance mechanisms are vital tools for achieving equitable access to, and provision of, ecosystem services

Rules, practices and institutions that govern the management and use of natural resources influence the provision and distribution of ecosystem services. Governance operates at multiple levels and includes individual farmers making choices about agricultural practices at the level of field and farms and modifying these practices over time; community organizations creating and maintaining forest or landscape management structures, national governments choosing where to direct investments in natural resources and water supply/management; and local customary or regulatory laws and policies on natural resource use. Interventions can be made in relation and across to all forms of governance to improve the long-term sustainability of ecosystem services, and the equitable access to services and their benefits, by encouraging, facilitating or enforcing changes to ecosystem use and management. To be effective, these interventions must take into consideration the biophysical structures and processes underpinning service provision [42] as well as the existing social context, and governance options [43]. Tackling this principle will require much greater and more meaningful research collaborations between the biophysical sciences which dominate ecosystem service research, and the social sciences [38].

Core principle 5: building resilience is about enhancing the capacity for communities to sustainably develop in an uncertain world

The fifth principle is both one of the most complex, and most important. Management options for agricultural systems are subject to, and must be responsive to constantly changing environmental and social conditions. In the absence of perfect information, resilience approaches are needed and emphasize the need to manage agricultural systems as complex adaptive socio-ecological systems with attention paid to component diversity and redundancy, connectivity, and slow variables and feedbacks [29,44]. Resilience of the socio-ecological system is maintained by securing capacity to learn and experiment, ensuring participation and supporting polycentric governance options. More than ensuring the specific resilience of agricultural systems to multiple externalities however, resilience approaches provide an embedded capacity to adapt food production functions of agriculture in the face of change. This should be carried out within the context of improving development outcomes for poor people over long time frames. This is particularly important at a time when increased global dynamics, can have profound effects on local realities [45].

Conclusions

Recognizing agriculture's dependence on ecosystems services calls into question the oversimplification of provisioning services in most ecosystem service assessments. Agricultural yields are all too often simply quantified as evidence of increased provisioning ecosystem services [46], whereas much of this yield is attained through the replacement (when possible) of regulating and supporting ecosystem services with external inputs [Figure 2, 15•]. This replacement drives many of agriculture's negative externalities or invisible costs [15•] and ignores most recommendations for managing resilience [29]. Using an ecosystem service and resilience approach in agriculture maintains human well-being through the provision of food and nutritional security as the principle system outcome, but emphasizes the contribution of regulating and supporting ecosystem services to this outcome—and thus emphasizes that sustainable food production is an emergent property of multiple interacting ecosystem services rather than a single service unto itself.

Reflections on agriculture's dependence on and contributions to ecosystem services provides important nuance to the land-sharing/land-sparing debate. While there is no doubt in our minds that critical conservation space must be spared from the plow [47], sparing agriculture from nature conservation negates both the dependence of agriculture on nature and the services it provides, and denies agriculture the capacity to contribute to sustainability targets other than food and nutrition security [15•]. Shared agricultural lands, in which conservation space is embedded through agroforestry, riparian buffer conservation, grass strips, field or land use diversification or other approaches are essential to secure biodiversity, both wild and managed, that underpin sustainable and resilient food production [22], and dietary diversity [32,48•,49]. Similarly, conservation objectives cannot be met without a shared agricultural space that provides both a space for wild biodiversity, and connectivity between spared protected areas [50].

Achieving agriculture's potential as the primary contributor to global sustainability targets will require a rapid rapprochement to recent transformation in conservation approaches as described by Mace [26••]. Over the past six decades, conservation has shifted from a focus on individual species conservation (1960s), to nature protection (1990s), and ecosystems service (2000s) approach. Mace [26••] argues that it currently considers a "people and nature" perspective-based on environmental change, resilience, adaptability, and social-ecological systems. The science of conservation biology, while retaining core disciplinary progress, is increasingly embracing interdisciplinary approaches and the social and ecological sciences. Agriculture is faced with a similar opportunity facilitated by using the ecosystem service and resilience approaches and allowing for convergence between agricultural and conservation sciences. This consilience is a necessary pre-requisite for agriculture to reach its urgently needed potential in contributing to multiple sustainability targets.

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See annotation for Steffen*et al.*, 2015.

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