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Biodiversity and agricultural sustainagility: from assessment to adaptive management

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Rapid changes in land use, food systems, and livelihoods require social–ecological systems that keep multiple options open and prepare for future unpredictability. Sustainagility refers to the properties and assets of a system that sustain the ability (agility) of agents to adapt and meet their needs in new ways. In contrast, sustainability tends to invoke persistence along current trajectories, and the resilience to return to current baselines. With three examples, the use and conservation of agrobiodiversity is explored along temporal, spatial, and human institutional scales for its role in sustainagility: first, farmers' seed systems; second, complex pollination systems; and third, wildlife conservation in agricultural areas with high poverty. Incentives are necessary if agrobiodiversity is to provide benefits to future generations.

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Introduction: the interconnection of three types of scale

With the advance of the anthropocene [1], human-induced environmental change is projected to increase due to population growth, higher per capita resource demands, and social changes, such as migration. Changes in land use, food systems, and livelihoods are now occurring so rapidly that there are no set formulas or routes for successful adaptation [2•,3•]. For example, meeting Millennium Development Goals (MDG) 1–6 (human well being) alongside MDG7 (sustainable resource use) is extremely problematic, especially in regions with an already limited and declining resource base [4–6]. The feedback loop between overuse of resources and climate change will add to the unpredictability faced by rural populations, despite agronomic interventions [7–9].

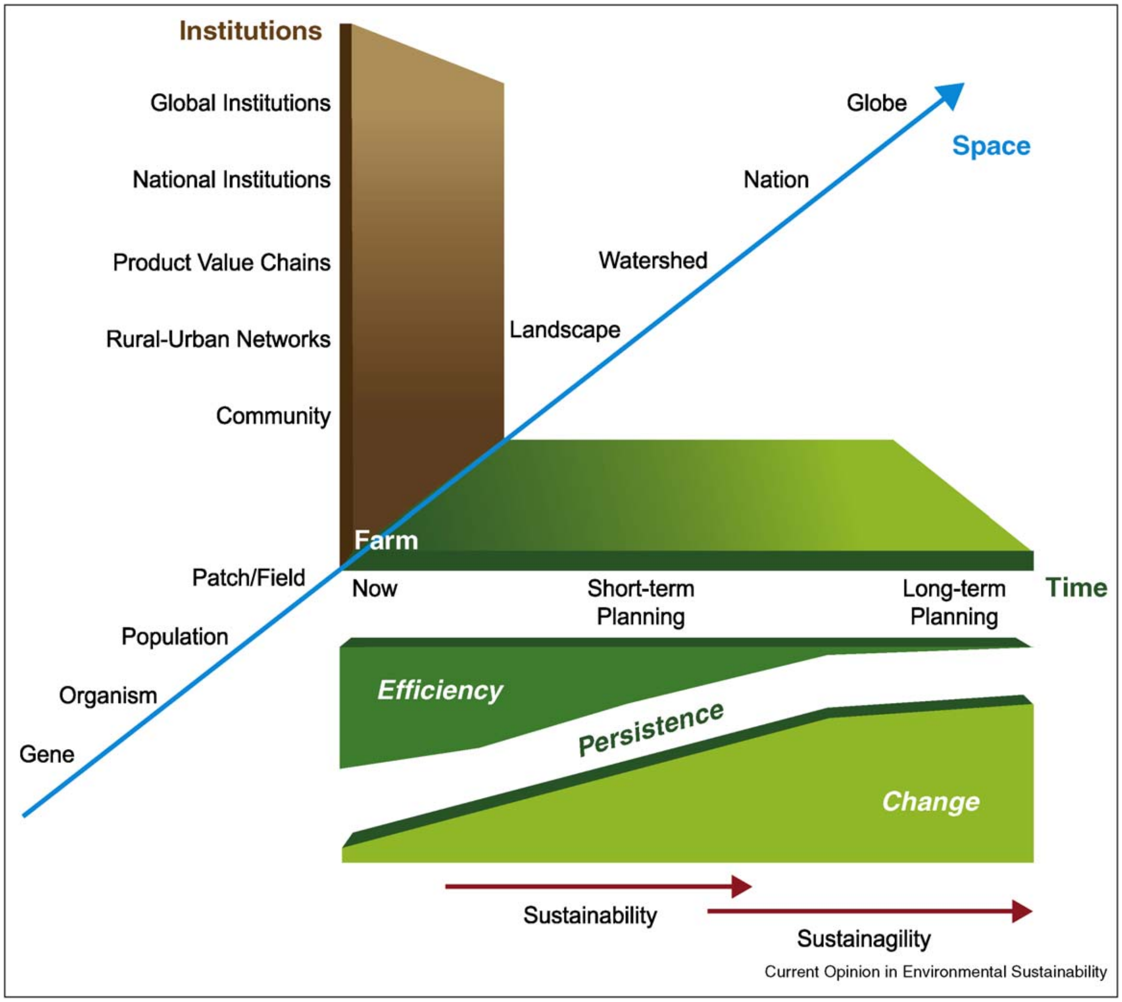
For ecosystems to remain functional and healthy, they must have the capacity to respond to unforeseen change. This requires keeping a number of options open, even if such a strategy is inefficient and suboptimal in the here-and-now. Maintenance of future options requires preparation for uncertainty, and for quick and agile adaptation, given the rapid pace of change. We use the term 'sustainagility' to emphasize the importance of developing strategies for adaptive capacity and transformability that consider tradeoffs at multiple scales [10,11••]. This is in contrast to simply sustaining the present conditions or systems through increased resilience, that is, the capacity of a system to experience shocks while retaining essentially the same functions and structures [12].

This paper focuses on how agrobiodiversity can influence sustainagility at three different scales in agricultural settings [temporal, spatial, and human institutions (Figure 1)], thereby affecting how people make management decisions and plan for future change. It also considers how current markets and other institutions can offer incentives for its use and conservation [13,14], including a short discussion on the role of schemes for payments for environmental services (PES).

Spatial scales

Agriculture is interpreted here broadly as involving crops, trees, and/or livestock in some form of domestication. Agrobiodiversity is not restricted to any taxonomic entity,

Figure 1



Three types of scale (time, space, and human institutions) and their relevance to planning for future uncertainty and the rapid pace of human-induced environmental change. Along the time axis, efficiency dominates planning in the here-and-now, while planning for persistence is aligned with the broad concept of sustainability (red bar), and the ability to rebound to current status. Preparing for change requires longer term planning to keep options open for uncertainty (despite unknown future implications of the current decision point), and thus is aligned with the broad concept of sustainagility (red bar). Farms are at the origin of the three axes (x, y, z = here-and-now, community institutions, farm), but their successful trajectory toward a sustainagility paradigm (x, y, z = future planning, regional to global institutions, landscape and beyond) requires communication with and support from higher institutional and spatial scales.

climatic or ecological zone, or habitat type, for example, grasslands, savannas, woodlands, and forests are all used for agriculture. Agrobiodiversity interacts with surrounding biodiversity through conversion of habitat, controlled reproduction of preferred species, tolerance of neutral species, and actions against undesirable ones [15•].

Farmers manage biodiversity at many scales, and their decisions are primarily driven by the private benefits they can reap in the here-and-now. Farmers tend to focus on provisioning services, which are generally the only class of ecosystem services that generate an economic return [16,17••]. Farmers and agricultural practices interact with different components of biodiversity at several spatial scales: from local fields and their surroundings; to the layout of agroecosystems at the farm level; and across the landscape at larger scales; influencing the dispersal and movement of organisms and their ecological functions. Greater awareness and integration of various spatial scales for planning and decisions will be conducive to sustainagility, for example, shifting from a main focus on the farm to greater focus on the landscape or watershed scales along the 'z' axis in Figure 1.

Temporal scales: efficiency, persistence, and change

Sustainability, defined as 'meeting current needs without compromising the future' [18], is a widely accepted goal across many sectors of society. But in practice, sustainability criteria and indicators often invoke persistence along current trajectories, rather than the capacity for

Table 1

Perspective on ecosystem services [11••] in agricultural landscapes and their association with different types of agricultural time frames

	Ecosystem services			
	Provisioning	Regulating	Cultural	Supporting
Efficiency	+++	+	+	()
Persistence	+	++	++	++
Change	()	+	+	+++

Supporting services underpin other types of ecosystem services, such as the genetic basis for evolutionary change.

change. Adaptive capacity and recovery from disturbance are likely to require radically different livelihoods and environmental management goals compared to simply continuing with present land use [19••]. Sustainagility, defined as the properties and assets of a system that sustain the ability (agility) of agents to adapt and meet their needs in new ways [10,11••], may be a more appropriate term describing the task of preparing for future unpredictability. Building and maintaining assets that keep multiple options alive requires emphasis on social–ecological systems and on interdisciplinary approaches that deal with the difficult issue of uncertainty.

This temporal framework involves three groups of concerns: first, the flow of goods and services in the here-and-now realm on which financial returns and efficiency are focused [17••]; second, persistence and continuity through investment in assets and stocks, upon which sustainability is focused; and third, human capacity to deal with change, to ensure future agroecosystem functioning in ways that include current likely options as well as those that are still unknown, that is, a sustainagility focus (Table 1 and Figure 1).

In the here-and-now, concerns for efficiency to achieve short run profits often dominate farmers' decision-making, hence the farm focus at the origin of the *x*, *y*, and *z* axes in Figure 1. For example, producers often aim for profitability of management actions and high returns on investment from inputs, rather than generating multiple functions in the landscape even when they themselves could benefit in the long run from such actions [17••]. Promoting efficiency at an immediate time scale has repercussions for both sustainability and sustainagility, since in the long run this could reduce efficiency and agricultural returns in the future.

Institutional scales

Biodiversity and ecological complexity have been recognized as key components for social–ecological resilience and adaptive capacity [11••,12,19••,20]. Option values exist in the context of environmental economics, but remain hard to quantify and incorporate. The concept of ecosystem services has helped to bring ecosystem issues into the realm of policymakers, but it emphasizes utilitarian, anthropocentric perspectives, and leaves intrinsic values and option values poorly represented.

Farmer attitudes and social networking are crucial for the innovation and conservation of biodiversity in agricultural landscapes. Farmers' investment in agrobiodiversity often involves opportunity costs of conservation or foregone benefits from land development [12]. Current markets and other institutions rarely offer incentives to promote management systems that support biodiversity as a public good, for example, for its option value for improving provisioning and regulating services in the future [21]. Social capital and collective action are often required to realize the public goods that can be generated from the use of agrobiodiversity; thereafter, adaptive management occurs through relations of trust, exchange, and connectedness [22].

Multiple drivers affect the behavior and cooperation of social actors (stakeholders and decision-makers) in agricultural landscapes [23,24]. Research at the household and community-level has clearly demonstrated the complexity and value of participatory frameworks for resilience to production shocks, for example, farmers' seed systems [25]. But scaling up to the landscape and regional levels, for example, assessing attitudes of various social actors in agricultural landscapes (such as interest in biodiversity and nature) along with variables describing biotic communities, ecosystem functions and production risks, is also needed [26,27]. The evolution of 'rules' in social–ecological systems [12] will determine how social actors will move from paradigms based on efficiency to sustainability and sustainagility. As shown in Figure 1, engagement of higher levels of human institutions (*x*-axis) to support long-term planning will be conducive to sustainagility. To develop contingent forecasts and scenarios for dealing with a range of outcomes under uncertain conditions, the effects of multiscale, multi-institution factors on farmer attitudes and social behavior must be better understood.

Contrasts between sustainability and sustainagility

Two of the following three case studies provide examples of use and conservation of agrobiodiversity within the context of efficiency, sustainability, and sustainagility.

The third example (on wildlife and poverty in Kenya) is included to show how lack of planning at multiple scales and institutions puts agrobiodiversity, human well being, and sustainagility at risk.

Management of crop diversity in West and Central Africa

Farmers' seed systems are based on farmer-bred varieties, and occasionally on modern, improved varieties, that are usually genetically diverse, and have traits of local value, such as tolerance to environmental stress, or preferred cooking quality or taste [28,29]. In the Sahel, farmers experience a high-risk environment because of large year-to-year precipitation and temperature variability, food insecurity, and health problems [7,8]. Many food crops in West and Central Africa rely mainly on farmers' seed systems, especially for pearl millet, sorghum, yam, and traditional leafy vegetables [30]. Yet farmers' seed systems are not officially recognized nor supported by governments and extension services.

In most emergency situations such as drought, civil strife, floods, locust invasion, or combinations of these factors, humanitarian relief practitioners and even national research or extension institutions generally have assumed that farmers' seed systems have collapsed or are inadequate. Yet field results show that farmers' seed systems are usually resilient and remain in operation [31].

Local systems of classification of seed traits reflect socio-culturally differentiated attitudes of farmers, who seek diversity and its functional attributes. The wealth of seed diversity and its associated knowledge is regulated by specific rights, responsibilities, and division of labor, often related to gender and age [25,32]. Relationships of trust and affection within the extended family, neighborhood or beyond, as well as norms, rules, traditions, customs, and practices influence the choice of seed by an individual farmer. In Burkina Faso, Mali and Niger, selling and buying seed from the markets is uncommon and seeds are often obtained as gifts [33].

In the Sahelian countries of West Africa, Bioversity International and its partners have provided training and infrastructure to strengthen opportunities for farmers to select and exchange varieties that they conserve [34]. Their Farmer Field Fora (FFF) approach (also known as Diversity Field Fora approach) is based on the assumption that overcoming rural poverty should be led by the rural poor themselves, by empowerment to develop more effective livelihood strategies to lessen shocks, and to increase the value of their assets. In Burkina Faso, Mali and Niger, farmers' groups tested both improved and local cultivars (Table 2a). Seeds of the selected cultivars were multiplied and disseminated within and outside the groups through seed fairs and seed banks. Preferred selection criteria by women and men farmers differed (Table 2b).

Table 2a

Number of selected varieties in Burkina Faso (Pobe Megao, Tougouri and Tiougou), Mali (Segou, Douentza, and Gao), and in Niger (Dan Saga, Elgueza and Guidan Tagno)

Crop	Country		
	Burkina Faso	Mali	Niger
Millet	2 (1)	6 (4)	3 (1)
Sorghum	1 (0)	4 (2)	3 (2)
Cowpea	4 (2)	5 (2)	2 (1)
Bambara groundnut	NT	2 (2)	NT
Peanut	2 (1)	1 (0)	2 (1)
Chinese senna	NT	NT	2 (2)
Okra	2 (1)	NT	NT

Brackets indicate local cultivars that served as initial germplasm. NT indicates that no testing was conducted.

Small farmers in West Africa have very small 'windows of opportunity' for change, and participatory approaches generate options that farmers are able to use [35]. Rather than technology transfer from outside sources, the FFF approach provides a means to achieve sustainagility using local genetic resources. Informal seed systems generate an evolving diversified genepool through networks of exchange and selection. In this drought-prone environment, the local seed system allows continued adaptation to meet changing conditions.

Insect diversity in oil palm plantations

Oil palm (*Elaeis guineensis*) is an enormously successful global crop, occupying over 13.8 million ha throughout the humid tropics [36] and providing raw products for food, consumer goods and, increasingly, biofuel [37,38]. The rapid expansion of oil palm monoculture plantations has been at the cost of natural forested areas [39] in some of the world's most biodiverse regions [40,41]. The conversion of forest to oil palm leads to significant losses of biodiversity but impacts vary for different groups of species and for subhabitats within oil palm plantations [42].

Biodiversity within agricultural ecosystems can be enhanced by structural complexity within the landscape [43•]. For oil palm plantations, this can be achieved through preservation of forest fragments, riparian strips, etc., and/or by providing habitat complexity within the plantation in the form of epiphytes and understory plants [42]. Complex habitats provide wildlife with shelter, breeding sites, additional food and other resources, stability, and the ability to recover from disturbance [44]. For the crop, conservation of biodiversity may contribute to economically important ecosystem services such as pollination.

Oil palm was thought to be wind-pollinated, but plantations outside of West Africa originally suffered from low fruitset and had to be hand-pollinated [45]. In Cameroun,

Table 2b

Some preferred selection criteria according to gender (for millet and cowpea from the African regions in Table 2a)

Crop/trait	Preference	
	Men	Women
Millet		
Height	Tall	Medium
Panicle size	Long	Long
Grain size	Big	–
Growth cycle	Medium	Short
Cooking qualities	Market demand	Suitable for local dishes and drinks
Cowpea		
Growth cycle	Short	Short
Grain color	Market demand	White
Insect resistance	Field	Field and in storage
Cooking qualities	Market demand	Short cooking time, good taste

where the palm is native, a suite of insects was shown to be capable of pollinating the crop [46]. The weevil, *Elaeidobius kamerunicus* (Faust), was the most effective pollinator. It was introduced into Malaysia in the early 1980s, and then to other oil palm producing countries, improving fruitset from 51% to 71% and revolutionizing the oil palm industry [47]. This dependency upon a single species to perform such an economically important service is, in fact, fragile and precarious. The present populations of *E. kamerunicus* have a narrow genetic base as they were derived from only a few pairs. Parasitic nematodes, for example *Elaeolenchus parthenonema* [48,49], and climatic extremes also cause fluctuations in populations [50,51].

For the persistence of effective pollination, new genotypes of *E. kamerunicus* could be introduced to strengthen the genetic base of the populations [49]. A complex assemblage of pollinating insects may be necessary [49,52]. Potential native pollinators exist in most areas [46,53,54]. The apparently sustainable ecosystem service of pollination that currently exists in oil palm plantations is probably not robust in the face of future, unpredictable change. Sustainagility would increase with greater genetic diversity within the chief pollinator species, the careful introduction of a range of related pollinator species, and increasing habitat complexity to encourage a diversity of native pollinators. Institutional support (e.g. from the Malaysian Palm Oil Board and Roundtable on Sustainable Oil Palm) for such interventions is likely necessary to move beyond efficiency and sustainability, and toward a sustainagility paradigm for greater resilience and adaptive capacity.

Wildlife and poverty in Kenya

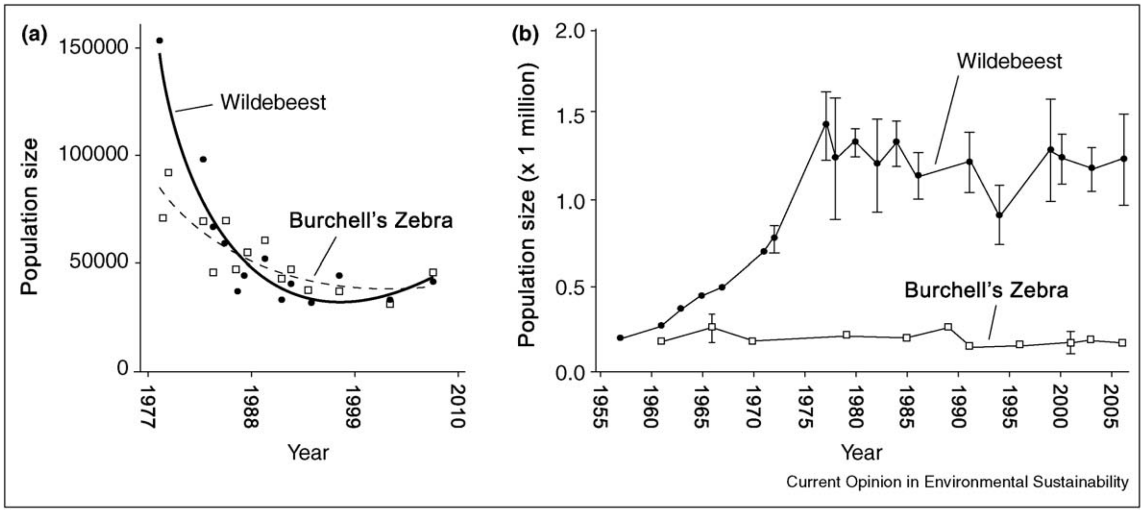
Kenya has invested heavily in a network of protected areas for wildlife conservation, which contain the great majority of Kenya's wildlife. But a high percentage (70%) of wildlife either permanently or seasonally lives outside these formally protected areas [55,56]. The abundance of wildlife on communal lands optimistically could present opportunities for local communities to economically benefit from these populations. Many of the communities living around these parks live in poverty (i.e. <1 USD/day) [57].

In the Serengeti–Mara ecosystem, large declines have occurred in 12 out of the 15 large nonmigratory herbivore species in the Mara, where more than half of the human population lives in poverty. For example, resident wildebeest and zebra declined by more than 90% in the last three decades (Figure 2a). In the Serengeti, which is a fully protected site, the population of many species has remained stable (Figure 2b).

Most of the wildlife declines have occurred in areas that were transformed to agriculture [58,59]. The returns from agriculture are far greater than those from either livestock or wildlife conservation for tourism, even in the areas of highest use by wildlife [55]. Recently, the decline of wildlife in some protected areas is as high as in communal areas [56,60], as a result of landscape interactions, further diminishing the potential for income generation from wildlife. Nevertheless, many of the communities in Kenya's rangelands have changed ownership from group ranches, or from communal to individual private land tenure, to consolidate their land to form wildlife conservancies, without a sound basis for future income. Land use in the Mara ecosystem is currently on a trajectory that is not sustainable for livelihoods and poverty alleviation, or for wildlife conservation.

Policy and institutional frameworks to expand conservancies are lacking in the area [61]. In some parts of Maasailand, however, a number of PES schemes are being tried, increasing wildlife numbers in some cases, and also conserving their habitats [55,56,62,63]. By recognizing that the custodians of wildlife are local communities under various land tenure systems, wildlife forums, and conservancies and associations, policies may be able to avert

Figure 2



(a) Trend of wildebeest (dotted symbol with continuous line) and Burchell's zebra (open square symbol and dotted line) in the Mara Ecosystem (*Source*: Kenya Department of Resource Surveys and Remote Sensing). **(b)** Trend of wildebeest (black dotted symbol) and Burchell's zebra (open square symbol) in the Serengeti Ecosystem (*Source*: Tanzania Wildlife Research Institute (TAWIRI) and Frankfurt Zoological Society (FZS)).

critical thresholds for wildlife declines. But these policies must be oriented toward 'pro-poor' benefits, and dealing with the complexity of efficiency versus equity issues, in order to be responsive to future social–ecological uncertainties [64], and to increase sustainagility.

Conclusions

Agrobiodiversity plays an important role in sustainagility, as it provides the biological sources (genes, species, and habitats) needed for adaptation and transformation to new production systems under unknown future environmental conditions. Fostering sustainagility requires understanding of ecological processes at spatial and temporal scales, as well as multiple knowledge systems for decision-making and enabling positive change for people. This will often build on ecological and institutional memory in a given biome [19••]. One form of incentives for farmers' use of agrobiodiversity is PES, for example, direct cash payments, price premiums on agricultural products, insurance, or land tenure. For most PES programs that involve crop and livestock producers, however, the income generated from the environmental benefit will only be a small share of household income, compared to profits from farm production [17••]. Other challenges are clarification of property rights and accurately linking actions to compensation [14]. PES may become most effective by leveraging other investment sources to promote multiple types of ecosystem services. Given that farmers are the largest group of ecosystem managers on the earth, emphasis on building multiscale institutions that increase social participation to use and conserve agrobiodiversity will lead to greater sustainability and sustainagility.

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