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Reframing the land-sparing/land-sharing debate for biodiversity conservation

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Conservation biologists are devoting an increasing amount of energy to debating whether land sparing (high-yielding agriculture on a small land footprint) or land sharing (low-yielding, wildlife-friendly agriculture on a larger land footprint) will promote better outcomes for local and global biodiversity. In turn, concerns are mounting about how to feed the world, given increasing demands for food. In this review, I evaluate the land-sparing/land-sharing framework—does the framework stimulate research and policy that can reconcile agricultural land use with biodiversity conservation, or is a revised framing needed? I review (1) the ecological evidence in favor of sparing versus sharing; (2) the evidence from land-use change studies that assesses whether a relationship exists between agricultural intensification and land sparing; and (3) how that relationship may be affected by socioeconomic and political factors. To address the trade-off between biodiversity conservation and food production, I then ask which forms of agricultural intensification can best feed the world now and in the future. On the basis of my review, I suggest that the dichotomy of the land-sparing/land-sharing framework limits the realm of future possibilities to two, largely undesirable, options for conservation. Both large, protected regions and favorable surrounding matrices are needed to promote biodiversity conservation; they work synergistically and are not mutually exclusive. A "both-and" framing of large protected areas surrounded by a wildlife-friendly matrix suggests different research priorities from the "either-or" framing of sparing versus sharing. Furthermore, wildlife-friendly farming methods such as agroecology may be best adapted to provide food for the world's hungry people.

Keywords: trade-off; agroecology; food sovereignty; population persistence; agricultural intensification

Introduction

Conservation biologists are devoting an increasing amount of energy and attention to debating whether land sparing (high-yielding agriculture on a small land footprint) or land sharing (low-yielding, wildlife-friendly agriculture on a larger land footprint) will promote better outcomes for local and global biodiversity.[1] Competing demands for land to produce food, fuel, fiber, and other resources place a critical constraint on nature conservation,[2] and these demands are increasing as the human population increases in size and affluence, leading to greater resource consumption[3,4] and greater urgency for biodiversity conservation. Therefore, determining how to reconcile agriculture and other extractive land uses with conservation is crucial.[5]

However, some authors have argued that the land-sharing/land-sparing debate is a "partial trade-off analysis" that is limited in the variables (goods and services) and societal values and preferences considered, and is thus not well suited to informing real-world land-use decisions.[1] This review evaluates the land-sparing/land-sharing (hereafter sparing–sharing) framework in terms of its utility for directing research and policy that can contribute to reconciling agricultural land use with biodiversity conservation. I evaluate the framework on five fronts. First, I discuss the terminology of the land-sharing/land-sparing debate. Second, I ask whether at the spatial and temporal scale of ecological field studies that have contrasted sparing and sharing it is possible to assess which approach best promotes

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species persistence (the key variable). Third, I ask whether agricultural intensification has led to land and/or nature sparing, and how environmental policy, socioeconomic context, and globalization influence these relationships. Fourth, since the sharing–sparing debate is often framed as a trade-off between global ability to protect biodiversity from extinction or feed the world's people, I examine what types of agricultural intensification can not only produce, but also deliver, food to the world's hungry.

Fifth, I reflect on whether the sharing–sparing debate, as an "either-or" dichotomy, may overly limit the realm of future possibilities for reconciling human food needs with biodiversity conservation. In the extreme, the land-sparing vision would lead to large nature reserves separated by a matrix entirely inhospitable to wildlife. Yet decades of research have pointed to the dangers of creating isolated nature reserves,[6–10] and conservation biologists have long recognized the potential positive role of the matrix for promoting connectivity, providing partial resources, and influencing the fate of species inside reserves.[10–15] In contrast, the extreme version of land sharing predicts a terrestrial land surface in which only tiny remnants of natural habitats remain, encompassed within wildlife-friendly agriculture. Again, decades of research have established that many rare, endemic, specialized, or area-demanding species require large expanses of wild habitats to survive and could not persist in such a fragmented landscape, and that trophic cascades and other ecosystem-wide effects can lead to rapid species loss.[8,16–22] Thus, the sharing–sparing dichotomy may force conservation biologists into a choice between two undesirable alternatives. Instead of an either-or framework, a "both-and" framework could lead toward a scenario that most if not all conservationists could get behind—large protected areas surrounded by a relatively wildlife-friendly matrix promoting connectivity through a combination of favorable land uses and corridors.[23–29] How to get there is a question worth asking, and getting there is a goal worth striving for. However, achieving this goal will require a shift in research priorities, away from evaluating whether land-sharing versus land-sparing landscapes achieve greater biodiversity conservation, and toward research that examines which matrix types favor species persistence in reserves and promote dispersal among reserves; how policies and governance mechanisms can be linked to reconcile agricultural production and biodiversity conservation; and which agricultural management techniques can simultaneously promote biodiversity and livelihoods.

The evolution of the land-sparing/land-sharing debate

The land-sparing argument goes back to Norman Borlaug, the architect of the Green Revolution. Borlaug claimed that since 1960, several hundred million hectares of lands were conserved from agricultural conversion due to broad adoption of Green Revolution hybrid varieties and chemically intensive farming methods that increased yields.[30] The land-sparing argument was combatted by Rudel *et al.*,[31] who found no empirical evidence for Borlaug's hypothesis that decreasing prices from rising yields led to contraction of the agricultural footprint. After accounting for land-market feedbacks and other complexities, Stevenson *et al.*[32] found that yield increases from the Green Revolution more likely resulted instead in 18–27 Mha of agricultural contraction, and only 2 Mha of avoided deforestation, two orders of magnitude less than the original Borlaug prediction.

More recently, the sparing–sharing framework was developed by Green *et al.*[33] and Balmford *et al.*[34] in application to species conservation. Taking both farmed and conserved lands into consideration, which form of agriculture would achieve a set agricultural output while sustaining the largest population sizes of the most species? The land-sparing strategy advocates segregating nature conservation from agriculture, using intensive, high-yielding agricultural production in one portion of the landscape to meet food demands, thereby freeing up lands for nature conservation elsewhere. The land-sharing strategy advocates accomplishing both biodiversity conservation and agriculture in the same landscape. Wildlife-friendly forms of agriculture would use organic and/or agroecological farming methods that promote on-farm biodiversity, and/or incorporate more small patches of natural habitat within the farming landscape. Wildlife-friendly modes of agriculture were assumed to suffer a yield penalty;[5,33] of course if they did not, then it was recognized that the combination of nature conservation with wildlife-friendly agriculture would be optimal.[5]

Table 1. Ecological studies of land sparing versus land sharing

Study	Where	Taxon	Biodiversity metric	Length of study	Extrapolate	Intensification metric	Reference condition studied	Results/ conclusion	Conclusions justified?
Land sparing is supported									
64	Choco-Andes, Colombia	Birds, dung beetles	Occurrence, species richness (α and β)	?	Yes	Proportion of forest fragments within cattle pastures	Forests	Using the same data as Ref. 43, the authors analyze how distance from forest influences the occurrence probabilities of species under sharing and sparing scenarios. They find that land-sharing strategies can support similar numbers of species as land-sparing strategies close to large forest blocks, but land-sparing strategies are superior across all distances.	Yes. A gap in the study is knowledge of the dung beetle and bird communities within the woodland fragments themselves, which were not factored into the simulations.
40[a,b]	Borneo	Birds, dung beetles, ants	Abundance, species richness	Four seasons	Yes	Amount of timber removed	Yes	A larger percentage of studied species would have higher abundances under a land-sparing strategy.	Yes, but over a longer time frame, the sparing strategy might lead to greater isolation of populations and extinction owing to loss of gene flow and rescue effects (henceforth listed as the "short-term perspective").
52[b]	Costa Rica; mixed forest coffee land-scapes	Birds	Species richness, diversity, and similarity	One season	No	Shade coffee versus integrated open canopy (IOC) coffee	Yes	Land sparing at the scale of small IOC farms (farms with sun coffee and a block of forest or equivalent area) works.	Yes, their results suggest that sparing at the scale of small farms would be better for wildlife, assuming profits from IOC versus shade coffee are similar, which was not addressed. Whether the same conclusions would extrapolate to much larger scales with large blocks of forest and sun coffee was not addressed by this study.
53[b]	Borneo	Birds	Abundance, species richness, species composi-tion	One season	Yes	Proportion of forest fragments within oil palm	Yes	Fragments within oil palm and oil palm itself has far lower abundance and richness of birds then contiguous forest.	Yes, but short-term perspective. However, in this case, even small regions of non-forest (>80 m) may arrest dispersal of forest birds, suggesting that land-sharing approaches might not help.
63[a,b]	Uganda	Birds	Population density	Two seasons	Yes	Food energy yield and income yield	Yes	More species, especially range-restricted species and species whose total populations are predicted to decline with increased agriculture, do better under a land-sparing scenario.	Yes, but short-term perspective.

Continued

Table 1. ***Continued***

Study	Where	Taxon	Biodiversity metric	Length of study	Extrapolate	Intensification metric	Reference condition studied	Results/ conclusion	Conclusions justified?
56[a,b]	India, Ghana	Birds, trees	Population density, species richness	1–2 years	Yes	Yield	Yes	More species, especially range-restricted species and species whose total populations are predicted to decline with increased agriculture, do better under a land-sparing scenario.	Yes, but short-term perspective.
172[b]	Ghana	Trees	Species richness	Three seasons	No	Management intensification index; yield	Forests	Cacao agroforests contained only 23% of the species richness of natural forests. Therefore land-sparing strategies are needed to conserve tree biodiversity.	Yes, but short-term perspective.
43	Choco-Andes, Colombia	Birds, dung beetles	Occurrence, species richness (α and β)	?	Yes	Proportion of forest fragments within cattle pastures	Forests	Changes in occurrence under land-sharing scenarios were much larger and negative for more species than under land-sparing scenarios, considering up to 80% of the landscape utilized for cattle production.	Yes, but short-term perspective. Studies of bird and dung beetles were not conducted within the forest fragments themselves, and these may be serving as stepping stones or providing habitat resources.
Land sharing is supported									
65[b]	Indonesia	Plants, insects	Species richness	One year	No	Percent canopy cover and relationship to cacao profitability	Yes	Transformation of forests to agroforests leads to a large biodiversity loss, but maintaining intermediate shade conditions greatly promotes biodiversity relative to full-sun cacao. Price differentials could be made up through wildlife-friendly cacao certification schemes.	Yes. Collected relevant socioeconomic data showing the feasibility of maintaining shade conditions within agroforests.
25	Argentina Chaco	Birds	Species richness	One season	No	Gradient of management intensification for cattle production, cattle live-weight per hectare year	Forest fragments >1000 ha	Intermediate intensity silvopastoral systems have only slightly lower species richness then large forest fragments and similar yields to high-intensity pastures; therefore, these wildlife-friendly measures should be adopted. However, forest fragments also need to be protected since not all forest-dependent species occur in silvopastures.	Yes.
88[b]	Indonesia, cacao agro-forestry	Plants, fungi, verte-brates, inverte-brates	Species richness	Two seasons	No	Yield	No	Biodiversity of nine target taxonomic groups was not correlated with yield, except for herbs, showing that	Yes. Shows that certain management practices could promote high biodiversity

Continued

Table 1. *Continued*

Study	Where	Taxon	Biodiversity metric	Length of study	Extrapolate	Intensification metric	Reference condition studied	Results/ conclusion	Conclusions justified?
								high yields and high biodiversity could co-occur.	without sacrificing yields. For example, while more shade reduces yields, shade can be decreased without sacrificing number and diversity of trees in the field, which were correlated with enhanced bird diversity.
66	Western Ghats, India	Plants, vertebrates, invertebrates	Species richness	Not applicable	No	Not measured	Forests	This meta-analysis of 17 studies in the Western Ghats found that human-modified environments supported similar levels of species to control forests. However, the amount of surrounding forest in the landscape was the most important factor influencing species richness levels. The authors conclude that it is important to protect remaining forest fragments.	Yes, but while the authors call this a “land-sparing” strategy, others would call the protection of forest fragments within human-dominated landscapes a form of land-sharing, illustrating the confusion generated by the sparing–sharing terminology.
62[b]	United Kingdom	Birds, plants, bumblebees	Species richness, rarity	One season	No	Not measured	No	Targeted agrienvironment measures led to enhanced species richness of bees, birds, and plants, including rare species in less-mobile groups (plants, bees).	Yes. Suggests that better biodiversity results can be obtained via “wildlife-friendly agriculture” without taking any more land out of production, as long as interventions are targeted.
Neither land sparing nor land sharing is supported									
24[b]	United States	Birds	Abundance	Two seasons	No	Not measured	No	Each of the six species studied exhibited a different abundance response to the micro-, meso-, or landscape-scale habitat attributes. Both wildlife-friendly farming methods and larger areas of grassland set-aside are needed for bird conservation.	Yes. Did not explicitly evaluate the biodiversity–productivity trade-off.
55[b]	Ugandan forests without hunting	Four primate species	Population densities	One season	No	Surrounding forest coverage; distance to main forest, distance to population centers	No	Primates can use mixed agroforest mosaics, sometimes (but not in all cases) attaining similar densities to forest. Agroforest mosaics can serve as buffers to protected areas.	Yes. Does not address the question of given a fixed crop demand, would it be better to have a larger reserve with high-yielding agriculture around it, versus a smaller reserve with mixed agroforests?

Continued

Table 1. *Continued*

Study	Where	Taxon	Biodiversity metric	Length of study	Extrapolate	Intensification metric	Reference condition studied	Results/ conclusion	Conclusions justified?
173[b]	Eastern United States	Plants	Species richness (β)	One season	Yes	Not measured. Instead a sharing scenario was constructed on the basis of the upper 95% confidence interval of the species-area curve for arable landscapes.	No	Benefits of land sparing versus land sharing depend on the initial amount of noncrop area.	Unclear. The sharing scenario was not related to yields or to farming practices. Further, land-sparing scenarios did not insist on contiguous land area for the spared lands. If such scenarios included small fragments protected across the landscape, they become synonymous with the land-sharing scenarios of other papers (e.g., Ref. 53).
61[b]	Australia	Bats	Species richness, activity, feeding buzzes	One season	No	Not measured	No	Remnant vegetation, native pastures, and trees within fields supported greater bat species richness and activity.	Yes. Does not address the question of given a fixed food demand, would it be better to have a larger reserve with high-yielding agriculture around it, versus a smaller reserve with remnant linear strips and trees within fields?
174[b]	Argentina	Birds	Species richness, population density, species composition	One season	No	Meat yield (estimated using forage-conversion or crop-conversion ratio).	Yes	Suggests that the most intensive land use, soy production, might spare the most land for nature.	No. The comparison between soy production, which ultimately is used in other countries to produce pork, and pastures and silvopastures in Argentina used to produce beef, is not a valid economic contrast, since those actors who are growing soy are not making the profits associated with the pork production elsewhere.
23[b]	Mato Grosso, Brazil	Birds	Species richness, species composition	One season	Yes	Not measured	No	Few forest-dependent species were found in countryside habitats, although the presence of relictual trees increased their occurrence. Thus, large protected forests are needed, but matrices including relict trees should also be promoted.	Yes. Does not address the question of given a fixed crop demand, would it be better to have a larger reserve with high-yielding agriculture around it, versus a smaller reserve with mixed agroforests?
Mixed: depending on context, either land sparing or land sharing could be supported									
60[b]	United Kingdom	Plants, earthworms, hoverflies, bumblebees, solitary	Abundance, species density	Two seasons	No	Yield	No	All groups except plants responded directly to changes in yield, and management (organic versus conventional) did not further explain	Yes, although the number of organic versus conventional farms that overlapped in yields was small. It could be that there

Continued

Table 1. *Continued*

Study	Where	Taxon	Biodiversity metric	Length of study	Extrapolate	Intensification metric	Reference condition studied	Results/ conclusion	Conclusions justified?
		bees, butterflies, epigeal arthropods, birds						abundance or richness patterns.	was insufficient power to detect the additional changes that management could provide.
51[a,b]	United Kingdom	Butterflies	Abundance, species richness	One season	Yes	Yield	Yes	A threshold organic to conventional yield ratio was estimated above which sharing is better and below which sparing is better. In this case, the sparing scenario consisted of high-yielding conventional agriculture with restoration of field margins.	While the authors interpret their results as supporting land sparing, restoration of field margins could constitute a sharing strategy according to many authors. Also, if no land is taken out of production, this strategy is not actually sparing.

[a]The study includes the metrics recommended by Ref. 5. All studies considered by Ref. 39 were reviewed here (indicated by[b]), and additional studies added using a literature search. Biodiversity metrics are α-scale unless otherwise noted.

The sparing versus sharing debate has since occupied an increasingly prominent place in the conservation literature,[27,35–38] although the number of empirical comparisons of wildlife responses to sparing and sharing landscapes remains small[37] (Table 1). The debate now refers not only to agriculture and biodiversity, but also to other land uses (i.e., forestry and housing[1,40,41]) and ecosystem services.[42,43] For this review, I focus on the original trade-off between agriculture and biodiversity conservation. Additional empirical studies examining the relationship between agricultural intensification and land use at global[31,44] or regional scales[45–47] have shown that there is no simple relationship between agricultural yield and land sparing due to the complexities of national policies and global markets.[48] Despite the small number of ecological studies, some authors[4] have prematurely concluded that the debate has been resolved in favor of land sparing: however, the debate cannot be resolved without also considering the land-use dynamics that play out in response to policy and market forces.[46]

Terminology of the land-sharing/land-sparing debate

The terminology used in the sparing and sharing debate has been used imprecisely or inconsistently, creating confusion. The term "land sparing" is often used to imply nature conservation, but land sparing is not the same as nature sparing, since these are independent processes that are not necessarily connected in space or over time.[46] While the land-sparing process may occur in response to yield intensification under some circumstances,[2,49] associated nature sparing generally requires environmental policies and/or formal declaration of protected areas.[50] Furthermore, land sparing, as in contraction of the agricultural footprint due to yield increases, could result in nature sparing at any scale or configuration, from dispersed field margins[51] and small forest fragments[52,53] to large, contiguous forest blocks.[54] However, land sparing in the sparing–sharing framework is intended to refer to protection of contiguous, large blocks of habitat.[5] When land is instead spared in small dispersed fragments,[52] this creates landscapes that would typically be identified as "land-sharing landscapes." The essential land-sparing argument, that is, that intensification of agriculture will free up land for nature conservation, both confounds land with nature sparing and leaves scale unspecified.

Authors also define wildlife-friendly agriculture in different ways—for some it means using practices that support biodiverse, heterogeneous agricultural systems that may or may not include forest fragments,[55,56] while for others, it simply means including forest fragments without any change in agricultural practices.[43,53] In the latter case, lands are being removed from production, leading to an obvious yield penalty, whereas in the former case, yield reductions are not a given.[57–59] Some authors use yield levels as a proxy for "wildlife friendliness," with low-yielding agriculture assumed to be more wildlife friendly.[5,51,56,60] Other authors determine wildlife friendliness of different landscapes on the basis of farming practices or heterogeneity of agricultural practices.[24,61,62] It is likely that both yields and wildlife friendliness are determined by the specific combination of agricultural practices utilized, and thus defining the sparing–sharing continuum with reference to agricultural practices, rather than yields, would reduce this inherent confusion (Box 1).

Do ecological field studies resolve the sparing–sharing debate?

The small group of empirical biodiversity studies explicitly conducted to compare sharing and sparing landscapes (Table 1) measured a variety of response variables (population density, species abundance or incidence, local species richness, regional species richness or turnover) for a variety of taxonomic groups, sampled across different biomes, continents, spatial scales, and farming systems, including those spanning thousands of years of cultivation to frontier zones.[39] Below, I first discuss state-of-the-art studies and contrast them with studies that collected less or different types of data from the best practices model.[5,56] I then consider the limits to inference from the state-of-the-art studies due to their bounded temporal scales. Next, I discuss the applicability of these results to conservation and land-use decision making, and finally, future research needs.

State-of-the-art studies

Phalan *et al.*[5,56] developed best practices for ecological studies contrasting sparing versus sharing. Studying a set of sites along an intensification gradient, they first developed population density—yield functions for *individual species*, to identify species that respond favorably to agriculture relative to no agriculture (winners) versus those that decline in response to agriculture (losers). Next, on the basis of the shape of density-yield curves, they classified species as favored by sparing (i.e., loser species whose densities rapidly decline in response to low levels of agriculture; winner species whose populations increase rapidly at the highest levels of intensification) or sharing (loser species that gradually decline or winner species that gradually increase in response to increasing agricultural intensification). Next, they determined how many species would obtain their highest population sizes across farmed and natural landscapes under sharing versus sparing scenarios for a given level of production and repeated these assessments across a range of production targets. Developing these predictions requires collecting data on species' densities across replicated sites that vary in yields, including reference communities; only a handful of studies have collected such data (Table 1).

Studies utilizing this research design[40,51,56,63] have generally concluded that the land-sparing approach benefits a greater number of species.[51] A key advantage of these studies is that they collect data on individual species densities and thus are more readily interpretable, since aggregate measures like species richness or diversity can mask underlying patterns, particularly of disturbance-sensitive species of greater conservation concern.[5]

Incomplete studies

Studies that did not collect some of these key data cannot necessarily be interpreted as supporting sparing or sharing. For example, studies that did not collect yield data do not evaluate the biodiversity-productivity trade-off.[23,24,61] Studies that evaluated biodiversity metrics only in farmland but not in the forest fragments that made up the "wildlife-friendly" component of agriculture may bias conclusions toward land sparing.[43,64] In some cases, different authors have come to diametrically opposed conclusions about whether a study supported sparing or sharing. For example, Steffan-Dewenter *et al.*[65] (p. 4977) clearly interpret their findings as supporting sharing, whereas in their review, Wehrden *et al.*[39] reinterpret these findings as supporting sparing. This lack of accord may be due to different definitions of what constitutes acceptable sharing; while Steffan-Dewenter *et al.*[65] observed similar diversity levels in agroforestry plots as in near natural forests, only ∼40% of forest-dependent species were found in the agroforestry plots. Similarly, field margin enhancements[51] or maintenance of small forest fragments[52,66] are considered examples of sparing by some authors, but others classify these as wildlife-friendly farming measures due to their small scale and integration within the farming landscape.[43,53]

Limited temporal scale

Although the state-of-the-art studies have yielded results that are readily interpretable,[40,51,56,63] these studies are limited in temporal extent and thus, in

Box 1. Finding agricultural practices that promote both biodiversity and yields or profit

Sharing or wildlife-friendly farming has been assumed to occur under conditions of low-yielding agriculture. Yet it is more likely the specific agricultural practices and suites of practices utilized, rather than the yields they produce, that determine how hospitable the shared agricultural landscape would be for elements of biodiversity.[60,88,129,153] These practices and systems (i.e., cover cropping, crop rotation, intercropping, agroforestry, conservation biological control, conservation agriculture, rotational grazing, and mixed crop–livestock systems) will also affect yields; some outproduce conventional systems (e.g., Ref. 59) or are equally productive or profitable, while improving conditions for biodiversity[153] and other ecosystem services.[128] Focusing on how specific agricultural practices or suites of practices relate to both yields/profits and biodiversity, rather than studying the yield–biodiversity relationship, would elucidate the important relationships while providing scope for management interventions.[65,88] Do certain practices enhance both yields/ profits and biodiversity? Do other practices enhance biodiversity without any effect on yields/profits?[93] How do different farming practices and systems promote or hinder species dispersal,[163] particularly for forest-dependent species?

For example, organic agriculture has well-known positive local[164,165] and landscape-level effects on biodiversity[166,167] in comparison to conventional agriculture, but may suffer reduced yields in many cropping systems.[60,157] However, organic management encompasses a wide spectrum of practices, from highly sustainable, diversified practices to less sustainable "input substitution."[122,168] The different practices used and styles of organic agriculture are likely to have different effects on both biodiversity and yields/profits. Diversifying practices like crop rotation and multicropping were found to reduce yield gaps for organic agriculture,[157] increase profit margins,[169] and enhance ecosystem services[128] and components of biodiversity (e.g., pollinators[170]).

inference. As snapshots in time (1–4 years, with most single year), these density-yield studies may not inform the long-term prospects for species persistence, arguably *the key measure* needed for assessing alternative land-use plans for their value for conservation.

Static estimates of population sizes under sparing or sharing scenarios do not explicitly consider long-term population dynamics and how these will be affected by patch-matrix interactions, including the positive and negative effects of the matrix on resource provisioning, dispersal, and the abiotic environment.[67] These effects are in turn influenced by habitat quality in both patches and matrices, spatial configuration of patch and matrix elements, and how these vary over space and time.[67] Thus, species that are predicted to do better under a land-sparing scenario based on density-yield curves may not persist over the long term, if, for example, high-intensity agricultural matrices restrict gene flow and rescue effects, leading to extinction.[36] Time lags for species extinction are long (i.e., $>\sim 300$ years for half of species in entirely isolated fragments >1000 ha to become locally extinct, or ~ 800 years for patches $>10{,}000$ ha) and extinctions have been documented across a wide range of fragment sizes (<1 ha to $>4\times10^6$ ha), even in avifauna, a relatively mobile group.[68] Thus, species judged to be favored by a land-sparing strategy, based on density-yield data, may already be committed to extinction within the studied natural habitat areas, unless these areas could be reconnected to other areas. Similarly, species that can occur in the matrix and are predicted to be favored by land sharing based on density-yield data may still require forest patches above a given size for some stage of their life history,[69,70] and thus may not persist without such patches. Longer time frames, and different types of studies that assess, for example, the quality of the matrix in promoting or discouraging dispersal,[14,71–73] providing resources[55,66,74,75] or acting as sink habitat,[76,77] would be required to assess how sparing or sharing strategies affect long-term persistence.

Data collected over longer time frames would permit estimation of additional key variables, persistence, and colonization,[78] in continuous and fragmented forest in response to agricultural matrix quality, that is, high- versus low-intensity agriculture. Such studies would provide a more complete assessment of how sparing or sharing strategies would affect individual species, taking into account matrix and/or configuration effects on meta-population dynamics. For example, using multiseason occupancy modeling that accounted for detection bias, Kennedy *et al.*[79] found in a 3-year study of insectivorous birds (a guild particularly sensitive to fragmentation[75]), that (1) patches in forested and agricultural matrices had lower extinction rates than in suburban or mining matrices, and (2) matrix type was a better explanatory variable than patch area or isolation in modeling occupancy dynamics. This study highlights how sparing–sharing studies could be designed in the future, although it admittedly sets the bar even higher than posed by Phalan *et al.*[5] However, except for the number of seasons sampled, most sparing–sharing studies of birds[23,56,63,64] used a similar sampling design to the Kennedy *et al.* study,[75] in number of replicates, replicate area and point counts/replicate, and one study also collected a sufficient time series (e.g., ≥3 years) for dynamic occupancy analysis.[40,80] In conjunction with other data on species traits, multispecies, multiseason occupancy modeling[81] can be used to assess the interaction between species-specific properties and extinction and colonization dynamics, permitting greater inference about how land-use strategies influence biodiversity. For example, in California, M'Gonigle *et al.*[82] found that a wildlife-friendly farming measure (hedgerows) introduced into intensively farmed areas not only promoted year-to-year persistence and colonization of bee species, but also particularly supported specialized species.

Applicability to conservation

Few studies have collected the data needed to determine whether land-sharing or land-sparing strategies can retain more biodiversity (Table 1). Most conclusive are those following the Phalan *et al.* research design;[5,56] yet even these are inadequate because they do not assess long-term effects on species persistence[25] and do not consider the critical socioeconomic context that actually determines whether intensification results in land *actually spared* for nature.[48] In general, these studies simply confirm earlier knowledge that many species are highly forest-dependent and require maintenance of primary or advanced secondary habitats for their survival.[18,19,22,83] These studies also confirm earlier findings[84–86] that substantial numbers of species thrive in agricultural habitats in some cases; indeed some species in ancient agricultural landscapes depend on traditional agricultural management practices.[66,87] Even in cases where substantial biodiversity occurs in agronatural landscape mosaics and sharing is likely to be a viable option, authors conclude that forests and other habitats will need to be protected to maintain certain species[25,66,88] and the maintenance of phylogenetic diversity.[89] One utility of these studies is to determine which management systems have no potential at all for promoting biodiversity. For example, in oil palm, small fragments set aside within plantations appear to offer no hope for mitigating the effects of oil palm agriculture on biodiversity.[53]

Studies conducted at the relevant spatial and temporal scales, both those considered here (Table 1) and the "higher bar" recommended to consider issues of spatial heterogeneity (Box 2) and persistence,[39] are expensive and time consuming to conduct. It would be useful to understand when such studies inform conservation planning and land-use decision making on the ground. In some countries, such as El Salvador, it is clear that this debate is not useful because there is so little forest left that El Salvador would have to both protect all of its existing forests and improve the landscape matrix through wildlife-friendly agriculture to promote connectivity, in order to contribute to a regional network for carnivore conservation.[26] Thus, in El Salvador, a "both-and" framing is more useful than an either-or framing for policy development. However, under other circumstances, ecological studies assessing the consequences of land-sparing versus land-sharing approaches might be useful to inform policy decisions. For example, in Brazil, a 2012 adjustment of the Forest Code now permits greater flexibility in how landowners achieve the required percentage of legally reserved forests on their lands. Within biomes and states, landowners that choose to deforest 100% of their land can purchase the development rights to equivalent land areas of landowners that have maintained forests in excess of the legal requirement.[90] Over 2 million hectares have been enrolled since the program began in 2013 (http://bvrio.org/site/index.php/mercados/florestal/cotas-de-reserva-ambiental, accessed 6/3/15). Ecological data on the consequences of consolidated (sparing) versus fragmented (sharing) set-asides could inform how these offset markets should be structured. For example, sparing could be encouraged by structuring offset markets such that only forests above a certain size would qualify for sale of development rights.[91,92] Several research groups are using models to investigate the ecological and economic consequences of different rules for structuring offset markets (K. Helmstedt and M. Potts, personal communication).

Future research

To meet the challenge of reconciling agricultural and other forms of production with nature conservation, ecologists and conservation biologists should focus their limited time, energy, and funds on studies that will inform concrete conservation and management plans. Future research might often be more applicable to the question of reconciling agricultural land use with biodiversity conservation if it focused on how specific management variables in the working landscape influence both biodiversity and yield (or profit, which is more relevant to individual land managers), instead of comparing broad strategies like sharing and sparing. For example, Clough *et al.*[88] identified management variables in Indonesian cacao agroforests that had positive influences on biodiversity without affecting yields. They also found that negative impacts of decreased shade cover on bird diversity can be mitigated by maintaining the number and types of trees, even while reducing shade to make cacao more productive. Similarly, Prescott *et al.*[93] found that removal of epiphytes in oil palm plantations did not increase yields and thus is not a management practice that should be promoted. Detailed studies of this nature are needed to determine which management actions can promote components of biodiversity without yield costs (Box 1). Studies of how agricultural practices and landscape types in the matrix influence sensitive species could include their effects on feeding and breeding resources and dispersal ability, as described in Driscoll *et al.*[67] Studies should also assess when protected corridors of natural habitat or designated wildlife crossings are required to promote species movements, when other land uses can promote such movements, or when a combination of corridors/wildlife crossings and other land uses can work.[94]

New studies can also be more applicable to the real world by embedding their findings within the local socioecological context. For example, in Indonesia, Steffan-Dewenter *et al.*[65] collected socioeconomic data showing that growers prefer relatively biodiversity-rich shade cacao agroforests to full sun plantations (although the latter provide greater yield and income), suggesting that certification schemes that ensure price premiums for wildlife-friendly cacao are likely to be popular and effective. Such information is useful for designing conservation programs for working landscapes to complement protected area establishment.

Finally, future studies should assess which management techniques in the agricultural matrix can best promote conservation inside nature reserves.[10] For example, Dorrough *et al.*[95] studied grazing intensification impacts on biodiversity in southeastern Australia. Increasing sheep stocking rates to free up more land for nature preservation would require phosphorus fertilization. Given the fragile soils, such management would likely reduce cover by native perennial herbs and shrubs, potentially leading to landscape level changes in soil acidification, salinization, weedy invasion and erosion, with ultimately greater negative consequences for native biodiversity than an extensive grazing system without fertilization.[95]

Has land sparing actually occurred in response to agricultural intensification?

Various authors have asked whether land sparing does actually occur in response to agricultural intensification, and how contextual factors, such as market or environmental policies, technology, and globalization affect the response to agricultural intensification. Below, I first examine global- and regional-scale studies, then how environmental policies and socioeconomic effects have affected outcomes, and finally, how displacement effects (leakage) occur at local to global scales. I finish by identifying some topics for future research.

Global- and regional-scale analyses

Global-scale studies have shown that there is not a simple negative relationship between yield increases and cropland area; once intensification occurs, the efficiency gains and/or profits achieved may encourage further expansion, either of the same crop or others, a phenomenon termed the *Jevon's paradox*

Box 2. Inference limited owing to too-small spatial scale

The limited spatial scale of sparing–sharing studies may also reduce the ability of ecological studies to assess whether sparing or sharing is best for biodiversity. Wehrden *et al.*[39] argue that measuring biodiversity at the plot scale (α-diversity), as most studies do (Table 1), may not appropriately capture the heterogeneity that is typical in land-sharing agricultural landscapes. For example, in a study that encompassed ecoregion- to biome-scale comparisons, Karp *et al.*[86] found that β-diversity was higher in low-intensity agriculture than high-intensity agriculture. Wehrden *et al.*[39] also suggest assessing γ-diversity as a potential indicator of "lasting, long-term change in diversity at a landscape level, across the sparing–sharing continuum." An issue with any approach (i.e., density-yield, occupancy modeling, β–γ diversity), however, is the length of time needed to achieve equilibrium across communities,[9,68] as well as the fact that both cropping patterns (i.e., rotations, fallows, crop choice) and land-use change (conversions among broad land-use categories) are also dynamic, continuing to influence ultimate equilibria,[15] should these even ever occur.

or *rebound effect*.[2,31,50] Ewers *et al.*[44] examined FAO country data on yield, cultivated area, and forest cover over a 20-year period for 124 countries. While they detected a small but significant negative trend between yield gains for 23 staple crops and area cultivated per capita for these same crops by country, this trend disappeared when they considered yield gains for these staple crops against the total area cultivated per capita, suggesting that intensification of staple crops then led to expansion into other crop types. Similarly, Rudel *et al.*,[31] analyzing FAO country data on changes in agricultural intensification and yield for 161 countries over a 25-year period for 10 commodities, found that the most common pattern for countries achieving yield gains was to expand their agricultural footprint. Taking into account these and other economic complexities, Stevenson *et al.*,[32] using a sophisticated global economic equilibrium model linked to spatially explicit data on land use, showed that land sparing due to Green Revolution improvements in yield was only 18–27 Mha (an order of magnitude smaller than predicted by Borlaug[30]) and, further, that avoided deforestation (i.e., nature sparing) would likely constitute only 2 Mha of the land-sparing effect.

Ewers *et al.*[44] found that countries with greater yield increases tended to have greater gains in forest cover; therefore some land sparing and nature sparing does occur and can be detected despite confounding factors. However, since land-cover data were not analyzed in a spatially explicit fashion, the "spared" land may be composed of small forest fragments rather than large land units, and may thus contribute more to shared than spared landscapes, illustrating again the ambiguities of the sparing–sharing terminology with respect to scale. Similarly, such analyses cannot distinguish the sparing of a unit of mature forest, versus the conversion of that forest and regrowth of a similar sized unit, although these two scenarios have different implications for biodiversity.[48] Rudel *et al.*,[31] examining additional socioeconomic variables, found that in the relatively few countries in which yield increases were associated with reduced cropland, countries imported grains and created policies incentivizing conservation set-asides. These policies, which included the Grain for Green program in China, agrienvironment schemes in the European Union, and the Conservation Reserve Program in the United States, "spare" land for nature within agricultural working lands, but often in a discretized spatial pattern typical of sharing rather than sparing landscapes.[96] In addition the amount of land spared by policies that operate over short time frames may change rapidly in response to changing market conditions, reversing previous conservation benefits[31]—as happened recently in the United States when biofuel markets increased demand for corn, causing growers to switch marginal lands out of the Conservation Reserve Program to replant corn.[97,98]

A major trend of forest regrowth is occurring across Central and South America.[49,99] Is this evidence for land sparing in response to agricultural intensification? While smallholder farmers may abandon their lands because they are unable to compete with industrialized agriculture,[49] this failure to compete should be evaluated in the context of market, institutional and political factors that result in an "uneven playing field"[99,100] rather than simply production efficiencies. Further, smallholder occupation of marginal agricultural lands (and subsequent abandonment) may reflect a history of dispossession that is related to agricultural intensification.[99] Thus, a deeper historical perspective is needed to evaluate the relationship between agricultural intensification and forest regrowth in Latin America. Again it is important to ask whether forest regrowth is resulting in large regions of contiguous forest (land-sparing landscapes) or many forest fragments with human settlements (land-sharing landscapes). While this varies among regions, many areas experiencing afforestation in Latin America have high settlement densities and utilize both forests and smaller regions of annual cropping for livelihood production.[99]

Effects of environmental policies

Many authors have suggested that land sparing and nature conservation will not occur in response to agricultural intensification alone, but require an enabling policy framework.[1,10,32,37,38] Analyzing agricultural data from six South American countries that include 94% of the South American tropical forest biome, a region that continues to experience high levels of deforestation, Ceddia *et al.*[50] found that not only the level of governance but also the *type* of governance determined whether agricultural intensification would lead toward an expanded (Jevon's paradox) or contracted (land sparing) agricultural footprint. In countries with good conventional governance (i.e., low corruption, high rule of law, high voice, and accountability), agricultural intensification led to an expanded agricultural footprint, presumably because good conventional governance favored the conditions for a market-oriented society. However, in countries with strong environmental governance (as indicated, for example, by the proportion of land area formally protected for conservation), agricultural intensification led to a contracted agricultural footprint. For example, through strong multiscalar environmental governance along with supply-chain interventions, Brazil has managed to both slow Amazonian deforestation by 70% since 2005, while increasing production of soy and beef from the region.[101] These findings suggest that strong governance alone will not ensure that agricultural intensification translates into nature conservation; instead strong environmental governance is required.

In the absence of such environmental policies, agricultural intensification can lead to sparing of land *without* nature conservation. For example, in Peru, government is incentivizing planting of oil palm to meet rising global demand. Highly capitalized growers with access to infrastructure and technology have developed large, high-yielding plantations while smallholders with less capital operate less productive farms. On the basis of the typical yields and rates of forest conversion for each type of grower, Gutiérrez-Vélez *et al.*[46] estimated that high-yielding farms require 64% less total land to produce the same amount of product, but such farms would convert 58% more old-growth forest than smallholders. Large, high-intensity growers apparently locate their extensive land holdings in old-growth forests, even though forest clearing is more expensive, because these lands have clear tenure and a single owner (the State), whereas already-cleared lands often have uncertain or contested tenure. In general, it is hypothesized that high-yielding agriculture will expand into primary forests rather than already cleared lands when large areas of unprotected forests suitable for agriculture remain, due to the reduction in transaction costs and social conflicts from negotiating with government alone rather than multiple landholders.[48] In contrast, strong forest zoning laws or policies, coupled with enforcement, can prevent the expansion of high-yielding commodity crop agriculture directly into forest, as occurred during the expansion of banana and pineapple production in Costa Rica following the passage of its 1996 Forest Law, and the expansion of soybean in the Amazon region since 2006 when Brazilian environmental policies and enforcement procedures were intensified.[48,101] These examples clearly show that it is critical for conservationists to promote national policies for protected area establishment and environmental governance in any areas where agricultural expansion is occurring.

Socioeconomic context

Whether agricultural intensification leads to an expanded or contracted agricultural footprint can also depend on the context, including cropping system, labor requirements, land rents, markets, trade, and technologies.[2,32,102] Agricultural intensification might relieve deforestation pressure from locally consumed crops if technology improves production, as occurred in the Philippines when irrigation improved lowland rice cultivation, shifting deforestation pressures away from fragile, forested uplands.[103] In contrast, for cash crops with rapidly expanding global markets (e.g., soy, oil palm, and others), intensification has resulted in the expansion of agriculture into primary forests in some of the most biodiverse regions of the world.[46,104–109] However, supply-chain interventions can improve environmental outcomes in highly consolidated markets, where a few large buyers can dictate producer practices. For example, the Soy Moratorium on Deforestation in the Amazon, which occurred in response to a campaign initiated by Greenpeace, has contributed to the reduction of deforestation in the Brazilian Amazon since 2006.[101]

Displacement effects

Even if high-yield agricultural expansion is confined to farmed or logged lands rather than near-natural habitats, this expansion can result in displacement of the preexisting agricultural activities elsewhere, leading to indirect land-use change. For example, expansion of commodity and other market crops in Vietnam within existing agricultural landscapes led to displacement of shifting cultivation to the forest frontier, enhancing deforestation.[110] Mechanization and other technologies (e.g., herbicide-resistant plants) associated with agricultural intensification also reduce labor needs, leading to unemployment, migration, and the possibility of enhanced habitat conversion elsewhere.[2] Although displacement of activities into natural habitats can be controlled by strong environmental policies and/or establishment of protected areas,[2] these protections themselves can displace agricultural activities to unprotected habitat areas (e.g., Refs. 101 and 111), a phenomenon known as leakage.

Leakage in response to environmental policies or market forces also occurs across country borders. Thus, in the United States, retiring lands from crop production under the Farm Bill's conservation programs led to increased production elsewhere,[31] a displacement of agricultural activities outside the United States. Similarly, forest regrowth in several countries in response to environmental policies has been linked to displacement of agriculture or forestry activities to other countries.[112] This phenomenon is also observed in oceans, where displacement of fishing activities from industrialized countries with strong fisheries policies, mostly in the global North, to southern countries without such policies, is well documented.[113] Land grabs, whereby a transnational corporation or country obtains rights to farm a large land area in another country, are a manifestation of large-scale displacement of agricultural use. These land grabs may occur in response to environmental policies that restrict land use at home,[2] depletion of arable lands due to cycles of nonregenerative, chemically intensive agriculture,[114] economic advantages of producing crops elsewhere,[108] or an imbalance between agricultural production potential and national food needs.[115] Such land acquisitions can be facilitated by countries willing to lease land cheaply to gain foreign investment.[116] Land grabs can both contribute directly to deforestation and lead to secondary displacements/ dispossession of original inhabitants,[116] which may lead to additional habitat conversion. A general concern is that many trans-border displacements may spare land and/or nature in less biodiverse temperate regions (e.g., US Farm Bill Conservation Programs or EU agrienvironment schemes) at the expense of more biodiverse tropical regions.[108]

Future research

Displacement appears to be not only pervasive, but also often multiscalar, and its ramifications can be extremely difficult to quantify across all scales at which they may occur. Various methods for studying displacement are discussed in Meyfroidt *et al.*[48] The multiscalar nature of displacements and their context dependence makes it difficult to predict the global net effect of national policies promoting agricultural intensification versus wildlife-friendly farming, although examples of displacement appear to have occurred in response to both (see above). Much remains to be learned about the causal mechanisms of displacements, and this could be a fruitful area of future research. For example, are environmental policies that promote wildlife-friendly agriculture (such as EU agrienvironment schemes or US Farm Bill conservation programs) chiefly displacing agricultural land use outside of country borders, or also within country borders? Are displacements also chiefly occurring among biomes, such as conserving temperate forests in developed countries at the expense of tropical forests in developing countries? What host and recipient country factors promote land grabs? How can international environmental policies be devised to minimize trans-border displacement effects?

Do trans-border displacements ultimately lead to better or worse environmental and social outcomes?

What types of agricultural intensification can deliver food for the world's hungry?

Many authors have noted that current global food production more than exceeds global population needs,[117] yet 800 million people are chronically hungry and as many as 2 billion people suffer from micronutrient deficiencies ("hidden hunger").[118,119] This paradoxical situation suggests that it is lack of access to food, due to lack of sufficient purchasing power or the means to produce food, that is the principal cause of world hunger, rather than insufficient global production. Global food needs are projected to double by 2050, if current demand trends continue, especially increased consumption of meat and dairy products.[3,120,121] Although future demand projections reflect increasing affluence, particularly in developing countries, it is likely the poorest people who will be further harmed by the expanded production of meat and dairy to meet this market demand. Indeed, diverting half of the grain crops currently used to feed livestock back to human consumption would provide enough food to feed 2 billion people.[121]

Seventy percent of the chronically hungry are rural farmers, mostly smallholders (https://www.wfp.org/hunger/who-are, accessed 5/20/15). One cause of their lack of food security is insufficient access to land (due to population increases coupled with increased inequities in land distribution[122]), while another is low soil fertility and crop productivity.[123,124] Smallholder farmers also contribute substantially to global food production, producing an estimated 50–70% of world food.[125,126] Because smallholders both constitute a large portion of the world's hungry and provide a large portion of the world's food, agricultural intensification pathways that improve small farmer livelihoods can directly address world hunger, while other pathways may not. Thus, tackling world hunger means both redressing the inequities in distribution of agricultural lands and promoting sustainable, low-cost agricultural methods that improve smallholder productivity without relying on expensive inputs. Below, I assess the potential for conventional, sustainable, and agroecological forms of intensification to contribute to smallholder livelihoods, and suggest policy needs.

Conventional intensification

Conventional intensification relies heavily on the use of external inputs, including hybrid or genetically modified organism (GMO) seeds, chemical fertilizers, pesticides, irrigation, and mechanization. It is responsible for large environmental impacts, including pollution, eutrophication, and greenhouse gas emissions.[127,128] It is often practiced at large scale for large markets, and may employ few people owing to mechanization. It is therefore unlikely to be a method that is well adapted for improving smallholder livelihoods (see also Box 3) and food security. First, reliance on purchased inputs may maintain poor farmers in a poverty trap, or may be impossible for smallholders to obtain or afford.[129] Also capital investment and increased land rents often associated with intensification[102] may lead to dispossession by poorer smallholders. Second, these approaches will continue to contribute to production of rapidly expanding commodity crops like soy, corn, canola, and palm oil, that are destined for livestock and biofuels production, or widely incorporated into processed food products. These products either do not feed the hungry, or, when they do, contribute to the growing global health burden of obesity,[27,117,121] which increasingly afflicts low-income people eating cheap, high-fat, low-nutrient diets. Further, these commodity chains chiefly profit a small number of multinationals that increasingly dominate access to agricultural land, inputs and markets, further enhancing the inequities responsible for hunger.[114,130]

Sustainable intensification

Many scientists have called for *sustainable intensification* as a mechanism for sparing land for nature while ensuring global food security and the environment.[38,131] Sustainable intensification was originally defined as increasing the yield output per unit of land while improving both environmental and social (livelihood) conditions,[132] and relied on principles of agroecology to establish resource-conserving systems that are based on promoting favorable ecological interactions within the agroecosystem, rather than purchased inputs.[128,133–135] These resource-conserving systems (e.g., agroforestry, system of rice intensification, conservation agriculture, management intensive rotational grazing, and conservation biological control) were

Box 3. Intensification and smallholder livelihoods

Land-sparing policies may lead to negative social consequences for smallholders. In Laos, a series of government policies promoted the transformation of a large landscape from a multifunctional mosaic comprising forests, fallows, and shifting cultivation to a land-sparing landscape in which a large nature reserve segregated protected forests from intensively managed agriculture with shortened fallow periods.[54] While this shift may favor endemic biodiversity (at least in the short term, since longer term effects on persistence are unknown), it has had negative consequences for livelihoods and resilience to environmental and market shocks.[54] Perhaps these negative livelihood consequences could have been avoided if the policies promoting intensification and forest protection had been accompanied by support for agroecological innovation in the agricultural zone, and if land-use planning had resulted from a participatory rather than top-down process.[171]

found to increase productivity and improve smallholder livelihoods relative to unimproved subsistence practices.[123,136,137]

However, the recent sustainable intensification rhetoric has been critiqued for inadequate attention to social equity that would ensure not only a just allocation of resources within and between generations, but also the participation of all sectors of society in determining how needs are met.[138] Instead of focusing on building local capacity for food production through inexpensive low-input, resource-conserving methods,[132,136] recent promotion of the concept, in academia[139] and trade (http://www.monsanto.com/improvingagriculture/pages/producing-more.aspx), focuses on capital- and input-intensive solutions to enhance resource use efficiencies, such as irrigation, precision agriculture, fertilizer application, and GMO seed[140] Such solutions, while often presented as responses to global hunger, suffer from the same issues described for conventional intensification, and may increase the number of chronically hungry or malnourished people, if they further enhance the inequities in resource distribution that are responsible for hunger today.[27,117] Ironically, land-sparing proponents advocate sustainable intensification as an efficiency mechanism for promoting the segregation of nature and agriculture,[38] although originally sustainable intensification was defined as integrating nature and agriculture.[136]

Agroecological intensification

Agroecological systems are knowledge, management, and labor intensive rather than input intensive, and aim to regenerate long-term agroecosystem properties (soil health, water storage, pest, and disease resistance) leading to sustainable, resilient systems.[128,135,141] They include a wide array of practices and systems some of which overlap with those promoted originally as sustainable intensification. Ecological[142] or agroecological[58] intensification refers to increasing productivity per unit of land or energy via farming methods that rely on knowledge and labor to promote and regenerate favorable biological interactions (Table 2). Substantial yield gains and livelihood benefits can be achieved through agroecological methods.[59,123,124,136,137,143] Agroecological methods can also be applied in large-scale farms in developed countries and maintain profitability relative to conventional approaches.[132,144] Altieri and Toledo[145] estimate that about 50% of smallholder farmers use agroecological methods, meaning there is still a great deal of room for extension of these techniques. Agroecological methods can create a more biodiversity-friendly agricultural matrix,[27,36,133,146,147] for example, by using agroforestry and silvopastoral systems to develop complex, multilayered habitats, and improve connectivity,[148] thus exhibiting potential for a "both-and" solution to the biodiversity-food trade-off.

Policy needs

Policies that reduce the relative advantages of large agribusinesses relative to smallholders (e.g., land reform, campaign finance reform, control of corporate monopolies, removal of subsidies, and trade policies favoring developed economies and large multinationals) may be more effective than increasing the efficiency of global production in combatting world hunger.[100,149] Simultaneously, targeted policies that promote sustainable intensification in its original sense[132] for small to mid-sized growers (e.g., access to microcredit, development and extension of agroecological

Table 2. Specific terminology for replacing land sparing/land sharing compounded terminology

Term	Meaning
Agricultural intensification	Increasing productivity (yield) of agriculture per land unit.
Agricultural expansion	Increasing the agricultural footprint of land use, which can be used with respect to high-yielding or low-yielding agriculture
Agricultural contraction	Decreasing the agricultural footprint of land use
Habitat conversion	Transforming a natural or seminatural habitat into another land use
Habitat protection	Protecting habitat with environmental policies or through gazetting of protected areas, resulting in nature sparing
Land scarcity	Refers to the conflict over land from all land uses, including, for example, agriculture, forestry, mining, and urbanization[1]
Sustainable intensification	Increasing productivity of agriculture per land unit while assuring environmental and social sustainability[132,138]
Agroecological intensification	Using farming methods that rely on knowledge and labor, as opposed to other inputs, to increase production of agriculture per land unit, and that promote and regenerate favorable biological interactions to produce food; requires assurance of environmental and social sustainability, as above.

techniques, infrastructure development, and market access) are also needed (e.g., Ref. 148). Agroecological intensification as a specific policy goal is an advance over recent uses of the term sustainable intensification.[139] Because agroecology is knowledge, management and labor intensive, and requires fostering of ecosystem services for success, it has great potential to promote small farmer livelihoods and intergenerational equity.[136,138] For these reasons, agroecological systems have been broadly adopted by major international movements, including the UN Right to Food Programme and the International Peasants Movement, as well as many specific country or region-specific programs (e.g., France, http://agriculture.gouv.fr/IMG/pdf/ProjetGB˙cle8a75db.pdf, accessed 6/8/15).

Envisioning a desirable future

The need for establishing large protected areas to protect rare species, habitat specialists, narrow-ranged endemics, and area-demanding species has been firmly established in the conservation biology literature for decades.[8,16–19] Similarly, conservation biologists accept that the "working lands" matrix around protected area is a critical factor that affects the viability of populations within reserves, as well as their ability to disperse among reserves.[12,13,15,75] Matrix quality, as well as corridors explicitly designed to encourage dispersal, are therefore critical elements ensuring long-term persistence of species,[67,150] and the connectivity provided by the matrix will become increasingly important as the effects of climate change intensify, causing species' climatic envelopes to shift.[151] Thus, conservation biologists need to continue working toward creation and maintenance of large protected areas, to connect them via corridors, and to embed them in high-quality matrices that also promote species dispersal. Since such matrices must also support human livelihoods and well-being, the key challenge is how to make the activities in the matrix (e.g., farming and forestry) both high yielding (or more importantly, profitable), sustainable, and favorable to biodiversity.[129] The answers will be crop, system, and region specific, and there is great scope here for conducting useful research (Box 1).

To be clear, the "both-and" framing is not equivalent simply to embracing wildlife-friendly agriculture in some portions of the landscape and high-intensity agriculture in others, as many authors have stated, although this may also be desirable in particular instances.[152] Instead, it requires identifying agricultural methods that are both productive and wildlife friendly,[25,153] while also establishing policies and governance mechanisms to establish protected areas and wildlife corridors,[129] promote sustainable, regenerative land uses in agriculture, forestry and other sectors, curb consumption, and either limit corporate consolidation when it contributes to unsustainable and/or inequitable land use, or work with powerful corporate entities to achieve sustainability. This vision is a tall order, and might require a massive and concerted effort to find common ground among advocates for disparate but related causes—from conservation and environment to food sovereignty, labor justice, antimonopoly, and land rights activists, among others.

Recommendations

Promote agroecological research and extension

Agroecology provides the most likely methods to create farming systems that support greater biological diversity and improve sustainability while being as or more productive than conventional systems simply because agroecological systems rely on beneficial biodiversity to produce many of the key inputs into crop production (e.g., soil fertility, pest control, pollination).[128,133] While many agroecological practices were invented by farmers and have long histories, new practices have been developed or old ones improved through scientific research. One of the best examples of the positive effect of research is the development of the push–pull system for controlling two devastating pests of staple grains in Africa, striga weed and stem borers. This system has now been adopted by 100,000 farmers in sub-Saharan Africa leading to more than doubling of grain yields, as well as many other ecological and social benefits.[59] Yet, the amount devoted to agroecology is a tiny fraction of the public funding (e.g., <2% in the United States,[154]) expended on agricultural research,[155] and a far smaller fraction considering both public and private funds, since the bulk of private research funds in agriculture are spent on crop chemicals and seed and biotechnology traits.[156] Public research funds should be allocated for optimizing agroecological systems for enhanced productivity so that yield gaps, when they occur, would not be an obstacle to their adoption (Box 1).[157] To promote adoption, public sector investment is also needed for providing education and extension services, as well as financing programs to assist farmers with initial costs of transitioning to agroecological farming systems.[148,158]

Replace an oversimplified framework

The land-sparing/land-sharing framing has become shorthand for both land-use dynamics that respond to an enormously complex socioecological system, and population and dispersal dynamics that respond to the complexities of patch-matrix composition and configuration. The sparing–sharing framework thus oversimplifies the interrelationships between agricultural practices, intensification, expansion, yields, biodiversity, land-use patterns, land and market feedbacks, deforestation, reforestation, global trade, environmental policies, governance, labor, sustainability, equity, and local and global food security into a biodiversity-yield trade-off. In its seductive simplicity, the sparing–sharing dichotomy lends itself to overly simplistic policy prescriptions, some of which may serve entrenched interests.[102] The sparing–sharing debate initiated an important conversation, but a more complete conceptual model and more precise and definable terms are needed now.[1]

Developing this conceptual model and refining terminology (see Table 2 for suggested terms) is an important task for conservation biology. Several excellent component models exist that provide a starting point. Meyfroidt *et al.'s*[48] conceptual model of commodity crop expansion, with its emphases on indirect land use–change effects and displacements, describes the response of complex land-use dynamics to social, environmental, economic, and political processes. Driscoll *et al.'s*[67] conceptual model of matrix effects on patch-dependent species describes how population and dispersal dynamics respond to patch matrix composition, configuration, and abiotic properties. Phelps *et al.'s*[102] conceptual model of how agricultural intensification, by enhancing land rents, interacts with conservation policies like REDD+, provides important insight into how agricultural intensification could backfire for conservation.

Figure 1 is a concept map for the "both-and" framing advanced here. It lists the main components and additional factors in four categories (markets, governance and policies, land ownership, and agricultural strategy), that influence attainment of three joint goals: protecting or restoring natural habitat, enhancing the quality of the surrounding matrix, and alleviating poverty and hunger. Figure 1 suggests interrelationships that need to be investigated to assist in crafting policies leading to these goals. This review, in particular, suggests the following hypotheses (1) In combination with strong, enforced environmental policies to protect natural areas, agricultural intensification (conventional or agroecological) leads to conservation, while without such policies, it does not; (2) Even if

COMPONENTS	ADDITIONAL FACTORS
MARKETS Local — Global	Elasticity of demand Trade Land markets
GOVERNANCE & POLICIES Strong governance Environmental policies — Strong governance alone — Weak governance	Agricultural policies Trade policies Environmental policies Labor policies Multi-scalar governance Multi-sectoral governance
LAND OWNERSHIP Public — Urban — Large versus small landholder	Land use history Colonization Indigenous rights Land tenure Land rent Land inequities Land grabs
AGRICULTURAL STRATEGY Agroecological — Conventional	Farming practices Yield/profitability Labor Inputs Biodiversity (on/off farm) Pollutants (on/off farm)
NATIONAL & GLOBAL OUTCOME INDICATORS Natural habitat protected or restored — Matrix habitat quality enhanced — Poverty and hunger alleviated	Displacements

Figure 1. Concept map of key components influencing three goals of a "both/and" scenario for reconciling agricultural and food production (purple). Any set of markets, policies, and land-use and agricultural-intensification schemes could be evaluated from their effects on natural habitat protected or restored, matrix habitat quality enhanced, and poverty and hunger alleviated. In addition to main components, additional factors that contextualize the main components are noted.

nature conservation occurs, if agricultural products have expanding markets, trans-border displacements lead to the destruction of natural habitats elsewhere; (3) Strategies promoting agroecological intensification will enhance habitat quality of the agricultural matrix, while conventional intensification will not; and (4) Similarly, agroecological intensification will alleviate poverty and hunger more than conventional intensification.

Craft multisectoral, multiscalar policy

To achieve both conservation and agricultural production goals, multisectoral policies (i.e., including, for example, agricultural, trade, and environmental) must be crafted that account for multiscalar impacts and displacements.[108] Implementing models of adaptive governance,[159,160] especially connecting individuals and institutions at multiple, hierarchical levels across sectors through participatory processes,[161] might be needed to accomplish this task. For example, in Brazil, national policies to reduce Amazonian deforestation led to the creation of the Critical Counties program, stimulating collective action within counties to reduce deforestation, in order to avoid blacklisting and interruption of access to government credit.[101] As ideas about adaptive governance are still young and controversial,[162] a rich scope of work is available for conservation policy research. Further, our understanding of what combination of social, environmental, economic, and political factors influence land-use outcomes is still limited, and several hypotheses have recently been advanced.[48,102] Testing these hypotheses and searching for underlying causal mechanisms would greatly aid the formation of effective policy; to maximize their utility, the specific research questions to inform policy should be jointly framed by policy makers and scientists in a trans-disciplinary process, that is, constructing new forms of knowledge that transcend disciplinary boundaries and/or include collaborations between scientific and nonscientific actors in substantive work.[161]

Conclusions

Reconciling land uses from agriculture, forestry, mining, industry, and urbanization with nature conservation is an increasing challenge in a growing, increasingly affluent world. The land-sparing/land-sharing debate has recognized this challenge but its framing is oversimplified relative to the complexity of the problem. Meanwhile, governments, nongovernmental organizations, and multinationals are already invoking land sparing for biodiversity conservation as a rationale for policies on agricultural intensification, even though such policies may ultimately further harm biodiversity[102] without leading to poverty alleviation. A new framework that orients research and policy toward the most productive science and policy questions and outcomes is urgently needed.

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Conflicts of interest

The author declares no conflicts of interest.

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