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REVIEW

# The variable paths to sustainable intensification in agriculture

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**Abstract**
Continuing environmental degradation amidst economic growth and population increase has underscored the desirability of pursuing sustainable intensification in agriculture. In theory, it would increase the volume of agricultural production without further degrading the natural environment or compromising the food security of the world's poorest people. In practice, difficult choices involving trade-offs between agricultural development and environmental protection have characterized most efforts at sustainable intensification. Against this backdrop, a series of studies have tried to identify an optimal strategy for sustainable intensification. This article argues that there is no one optimal strategy. Rather, optimal strategies vary across socio-ecological contexts. Distinct strategies of sustainable intensification have emerged (1) in peri-urban agriculture, (2) on large farms situated on prime agricultural lands, and (3) in smallholder-dominated agricultural districts. Government interventions to promote sustainable intensification should recognize and build on these distinct, place-based economic, and agro-ecological dynamics.

**Keywords** Sustainable intensification · Agriculture · Trade-offs · Peri-urban agriculture

## Introduction

During the past ten years, "sustainable intensification" has become widely regarded as the necessary path for agricultural development under the difficult circumstances of climate change, population growth, and continued economic development (Rockström et al. 2017; Pretty 2018). Projected, near-term increases in the size and affluence of the human population argue for expanded agricultural production, but the expansion would need to occur without further degrading the natural environment, and it would need to secure adequate supplies of food for the world's destitute peoples. With these requisites in mind, a series of analysts have during the last decade tried to identify an optimal global path for sustainable intensification. This analytic strategy has encountered difficulties. In theory, sustainable intensification occurs when agricultural production on a tract of land increases at the same time that the agro-ecology of the larger landscape becomes more robust (Pretty 2018). In practice, efforts at sustainable intensification often generate trade-offs in which gains on one dimension, like agricultural production, offset losses on another dimension, like environmental conservation.

Faced with these ubiquitous trade-offs, analysts of sustainable intensification have recently begun to take an issue with optimization approaches, arguing that there is no generally "superior" form of sustainable intensification. Rather, the optimal form of sustainable intensification will vary from situation to situation or context to context (Butsic and Kuemmerle 2015; Mehrabi et al. 2017; Luskin et al. 2018; Egli et al. 2018; Thomson et al. 2019). By implication, there should be various situation-specific paths to sustainable intensification. This paper describes three of these context dependent paths to sustainable intensification.

The paper begins with an initial discussion of the trade-offs that hamper most efforts at sustainable intensification. These trade-offs explain why sustainable intensification in agriculture is more sought after than achieved. It takes place when location-specific synergies in agro-ecology and economics deliver benefits to both plants and people. Descriptions of three such synergies follow the discussion of trade-offs. The synergies occur in peri-urban places, in belts of prime farmland, and in smallholder agricultural districts. These descriptions provide a grounded view of the circumstances that foster

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different kinds of sustainable intensification. The paper concludes with a discussion of the situation-specific ways in which governments could intervene to expedite sustainable intensification in agriculture.

## Trade-offs in the sustainable intensification in agriculture

People encounter trade-offs when they realize gains in one valuable activity at the cost of diminished accomplishments in another valued activity. The trade-offs in agriculture often achieve improvements in the human food supply at the cost of declines in the natural environment. For example, enhanced production on large farms, if it comes through an expansion in agricultural lands, often destroys forests, expands greenhouse gas emissions, and accelerates biodiversity losses (Gibbs et al. 2010). Sometimes, the trade-offs pit global versus local food supplies. When a large-scale farmer decides to produce more foodstuffs for the global market, she/he contributes to the food security of distant populations at the same time that she/he impairs the food security of the local population. More of the production from the farmer's lands goes to faraway consumers rather than to local residents (Borras et al. 2011).

The most frequently discussed paths to sustainable intensification, one referred to as "land sparing" and another called "land sharing" (Phalan et al. 2011; Pearce 2018), both generate trade-offs that diminish their effectiveness. Land sparing approaches concentrate intensified agriculture on prime farmland. Cultivators on these lands invest in irrigation, genetically modified seedlings, and other capital-intensive innovations in an effort to raise already high rates of agricultural production even higher (Thomson et al. 2019). Through enhanced production on these lands, these farmers drive agricultural commodity prices lower. The low prices, in turn, drive other farmers on marginal lands out of business. The abandoned, agricultural lands are "spared" environmentally (Pearce 2018). The environmental gains do occur, but only on distant lands where competing farmers only see the lower prices from expanded production and reduce the scale of their agricultural operations. On nearby lands, the intensified production can exact an environmental cost. The neighbors of the intensifying farmer see the additional profit opportunities of the new agricultural technologies, so, in a rebound effect (Jevons 1865), they expand their use of the new technologies and the size of their agricultural operations. The local environment suffers from their agricultural expansion (Hertel et al. 2014).

In the contrasting "land sharing" protocol, shifting cultivators plant a mix of tree and root crops in the understory of a forest. These plantings enable farmers to harvest crops while maintaining forest cover on their lands. In this sense, the crop, the trees in the overstory, and the wildlife "share" a biome (Tscharntke et al. 2012). Land sharing typically reduces crop yields, compared with chemically driven conventional agriculture, so widespread adoption of land sharing would presume an extension of the agricultural land base in order to feed the world's population (Green et al. 2004). Some environmental services might persist with the continued forest cover on the shared lands, but agriculturally related degradation in these agro-forests would grow with the extent of the shared lands, so again trade-offs would characterize a landscape experiencing sustainable intensification.

Comparisons of these two modes of sustainable intensification have convinced many analysts that the land sparing approach would produce more sustainable intensification than the land sharing approach (Phalan et al. 2011). While this conclusion about the relative merits of land sparing and land sharing as strategies for sustainable intensification has empirical support, it loses some of its force because both approaches involve trade-offs that diminish the overall gains from a strategy.

Exceptions to this pattern in which losses offset gains occur when changes in the food system have synergistic effects on one another. For example, a growing taste for plant-based foods among urban residents might coincide with the creation of nearby farmers' markets that make it possible to deliver large volumes of high-priced, leafy green vegetables to market without significant post-harvest losses. These situation-specific synergies often have a geographical basis, and their presence makes particular kinds of sustainable intensification possible in different sets of places. This paper tries to trace out these links between strategies and situations.

What then are the situation-specific factors that might facilitate the different types of sustainable intensification? The growing proximity of farms to expanding cities, the changing size distribution of farms, the introduction of new technologies, and the creation of agricultural assistance programs by governments and NGOs could potentially give rise to synergies that would promote sustainable intensification. I review the influence of each of these factors on sustainable intensification efforts below. Then, I develop an argument about the ways that these contextual forces combine to create three distinct, place-specific trajectories of sustainable intensification.

## The changing contexts for sustainable intensification

**Urbanization** A pronounced concentration of humans in cities has accompanied the tremendous growth in the size of the human population from 3 billion persons in 1960 to 7 billion persons in 2011. If current rural to urban migration trends continue, every region of the world will contain more urban than rural residents by 2030 (Montgomery 2008). The growth in the size of urban populations has spurred a corresponding worldwide expansion in the areal extent of urban areas and

their surrounding peri-urban zones. Fig. 1 depicts the expansion in the size of peri-urban areas between 1970 and 2015.

The growing numbers and proximity of urban residents increase the local demand for agricultural products, which in turn provides the impetus for nearby farmers to intensify their operations (Tacoli 2003; Simon 2008; Zasada 2011). Some farmers, working on diminished acreage after the conversion of some of their lands to urban uses, continued to cultivate crops, but they do so in an intensified way. Other farmers, farther from the urban core, begin to sell their harvests at newly established farmers' markets on the fringes of urban areas.

Because urban residents are wealthier than rural residents, growth in the numbers of urban residents has contributed to changes in diets. Recent rural-urban migrants in the developing world have spent some of their increased income on more animal protein (Ramankutty et al. 2018). Slower growing populations of urban residents in the wealthier, already industrialized countries have recently spent more of their income on high-priced fruits and vegetables (MacKendrick 2018). Both of these consumer trends could shape the extent of farmers' reliance on urban and peri-urban markets as sources of revenue.

Central place theory (CPT), first articulated by Von Thünen during the nineteenth century, offers a potentially fruitful way to understand the dynamics of sustainable intensification in an urbanizing world. CPT asserts that land rents climb as the distance to an urban center declines (Von Thünen 1967). These differences in land rents, associated transportation costs, and proximity to large populations of consumers largely explain why the the intensity of land uses grows as access to central places increases. These shifts in agricultural practices would provide opportunities for sustainable agricultural intensification. For example, the shorter supply chains from farmers to consumers would reduce spoilage and allow farmers to grow more lucrative crops. As noted above, leafy green vegetables with profit margins as much as 30 times the profit margins of other agricultural commodities become

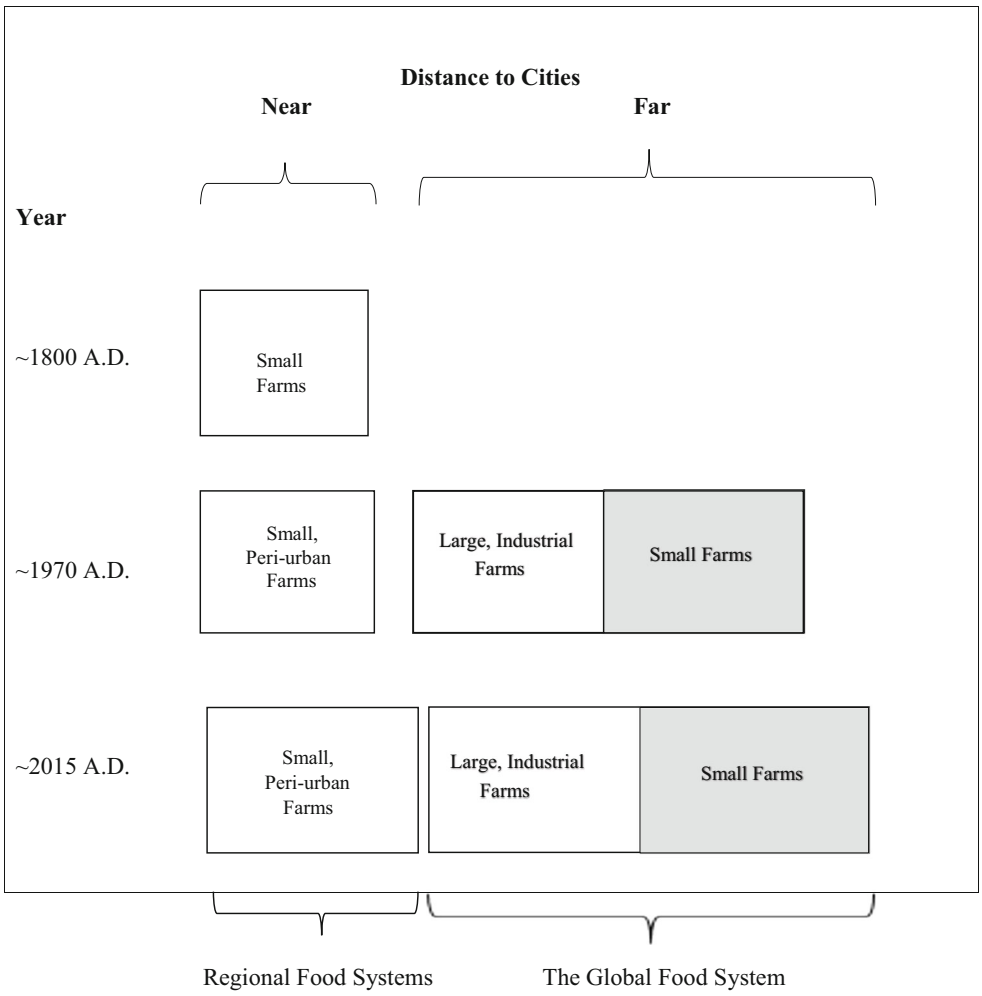


**Fig. 1** Cities and the changing spatial organization of the food system. Although small farms are situated farther from cities than are large farms, they are both meant to be "far" from cities, with one no farther than the other from city centers

possibilities in the crop mixes of peri-urban farms when transport to market takes little time (Lovell 2010; van den Berg, van Wijk, Van Hoi 2003).

**Neo-liberal states and declines in agricultural extension services** States, particularly in the developing world, have undergone transformations during the past forty years in ways that would affect processes of sustainable intensification. Debt crises spread across the developing world during the 1980s, followed by agreements with the International Monetary Fund to cut government services. States became less interventionist (Babb 2013). Parastatal marketing organizations disappeared, and state-supported services for rural peoples declined in extent (Grindle 1986). Extension services for farmers lost funding, and, as noted by many observers (Reardon et al. 1997; Koning and Smaling 2005; Hazell and Wood 2007; Settle and Garba 2011), both the number and effectiveness of extension interventions declined in sub-Saharan Africa and elsewhere. Planners frequently assumed that private companies would replace government-funded fertilizer and seed distribution services, but in many instances, private firms did not fill these market niches because the anticipated profits were too small (Reardon et al. 1997). It became more difficult for smallholders to acquire titles to their land during the 1980s when governments stopped subsidizing the acquisition of titles (Rudel and Hernandez 2017). After the cut in subsidies, only people with claims to large amounts of land or to valuable land near urban centers would pay for titles to their land (Alston et al. 1999). Public and non-profit support for agricultural research also declined (Pardey et al. 1995). These trends negatively affected outreach efforts to impoverished smallholders in rural settings. Considered together, these trends underscore the low level of investment in improving smallholder agriculture in the developing world after 1980 (Kiers et al. 2008).

**Increases in agricultural productivity** The past fifty years saw a green revolution in agricultural productivity. Larger applications of fertilizer, more precise, irrigated applications of water, and more frequent cropping of fields increased the productivity of croplands by 28% between 1985 and 2005 (Foley et al. 2011). Much of the expanded production in crops became animal feed, especially in affluent regions like North America. The growing salience of animal feed as an agricultural output and the large expanse of land devoted to animal husbandry underscores the potentially salutary environmental effects of a change in the human diet away from the consumption of large amounts of meat (Seufert and Ramankutty 2017; Mehrabi et al. 2017; Meyfroidt 2018; Winders and Ransom 2019). Sustainable intensification could be achieved through increases in the production of crops and declines in the production of livestock.

**The changing size distribution of farms** Two recent, global-scale analyses clarify how trends in farm sizes may have shaped efforts at sustainable intensification in agriculture. First, the size of farms appears to be diverging between wealthy and impoverished societies. In wealthier societies, farms have consolidated, with median farm sizes increasing. In poorer societies, in Asia and Sub-Saharan Africa, farms have gotten smaller, largely through the division of farmlands at inheritance (Lowder et al. 2016). Because farm size plays such an influential role in shaping agricultural operations, these diverging trends could generate distinct trajectories of sustainable intensification in large farm and small farm districts. A second analysis (Samberg et al. 2016) underscores the likelihood of these distinct, place-specific trajectories. Samberg and her co-authors (2016) matched MODIS derived cropland data with farming household data from population censuses in African, Asian, and Latin American nations. Samberg and her collaborators found distinct large and small farm agricultural districts, as displayed graphically in Fig. 1. For example, large farms characterize interior Brazil, while small farms predominate throughout extensive areas in South and East Asia. The prevalence of similar sized farms in a region increases the likelihood that neighboring farmers will copy innovations from one another. Because the substance of these innovations vary with the size of farms, small-scale farmers copy innovations from one another and large-scale farmers do likewise with each other. In this manner, distinct trajectories of sustainable intensification emerge in large farm districts and in small farm districts.

The contrasting trends in farm sizes between wealthy and impoverished agricultural districts need to be seen in the context of substantial historical shifts in food systems during the past two centuries. At the outset of the nineteenth century, smallholders dominated the production of foodstuffs. Large numbers of small farmers produced crops for consumption in their own homes or in nearby villages, towns, and cities (Wrigley 1969; Braudel 1973). Inputs to enhance productivity, like manure or regrowing vegetation, came from local sources. This smallholder-dominated, locally focused agriculture created a regional food system (see row 1, Fig. 1). Throughout the nineteenth and twentieth centuries, an alternative, industrialized food system emerged. It featured large-scale farms, mechanized farm implements, chemical inputs to enhance agricultural productivity, and long distance trade in agricultural commodities. At the same time, settler colonialism created middle-sized farms across large rural areas in the Americas, Eurasia, and Australia. Mechanization in the cultivation of cereals spurred further expansion and consolidation among these farms. These large, mechanized farms only sprang up outside of metropolitan areas where land remained relatively inexpensive and at the same time accessible to the major urban markets of the world (see rows 2 and 3, Fig. 1). Long distance supply chains tied these farms to cities.

Agricultural inputs and harvests traveled up and down these commodity chains between farmers and consumers. The farmers, processors, and consumers had created a global food system. Smallholder agriculture persisted within this global system (see rows 2 and 3, Fig. 1), often, but not always, in places far from cities, with rugged terrain and substandard road access. These small farms continued to produce most of the vitally important cereal crops like rice, cassava, and potatoes (Samberg et al. 2016; Herrero et al. 2010).

## Three trajectories of sustainable intensification in the twenty-first century

The observations, above, about urbanization and the size distribution of farms suggest that sustainable intensification will proceed differently in three distinct spatial arenas: peri-urban zones, large farm districts, and small farm regions. These types of sustainable intensification will vary in their geographical scale (Fischer et al. 2014). Sustainable intensification in peri-urban places entails a relocalization of agriculture to fields just outside of cities. Sustainable intensification on large industrial farms with more precisely applied inputs produces harvests that go to distant cities and induces the abandonment of marginal agricultural lands in remote sites in other regions. Given these patterns, the effects of sustainable intensification in industrial farming occur on a global scale. Smallholder-dominated rural districts produce crops through sustainable intensification that go to both local and extra-local markets. Sustainable intensification in these places produces local environmental gains in the enhanced agro-biodiversity of the small fields, the hedgerows between farms, and the groves of fruit trees around homes. These patterns suggest that smallholder-led sustainable intensification in rural districts has effects at both local and global scales. The following pages provide descriptions of the socio-ecological logics that drive each of these variants in sustainable intensification. The path diagrams in Figs. 2, 3, and 4 outline the social and ecological dynamics that produce the different varieties of sustainable intensification in each place.

### Locavores, plant-based diets, and farmers' markets in peri-urban places

As suggested in Fig. 1, the spatial extent of peri-urban agriculture has grown during the past fifty years as urban areas have become more populous and expanded outward in size. Growth in the numbers and proximity of urban consumers to small farms triggered sustainable intensification in peri-urban zones. Supply chains for food shortened, and food security increased. Farmers made more use of urban waste, and their incomes went up. Plant-based diets became more popular among consumers. This dietary shift, when large enough, induced land sparing in distant places by reducing demand for livestock and pastures (Daniels 2010). Fig. 2 and the following paragraphs outline the socio-ecological logic behind these synergies.

Small, peri-urban agricultural landholdings encourage more agro-biodiversity in cultivated areas. The proximity to large urban markets for agricultural commodities encourages farmers to diversify the range of agricultural products that they cultivate and sell (Tiffen et al. 1994). Diversification makes sense for producers in close proximity to large markets because the large size of these markets insures that farmers will find sufficient demand from urban consumers for a wide range of specialty crops (Wästfelt and Zhang 2016).

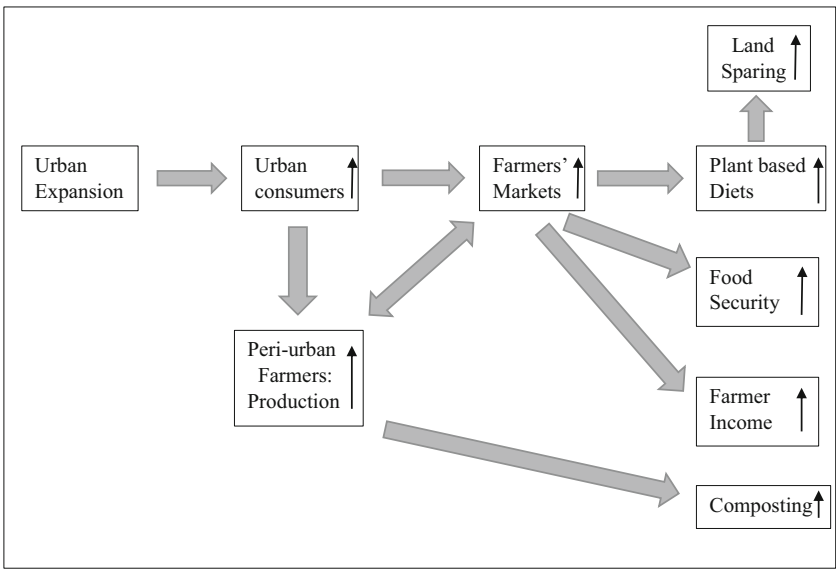


**Fig. 2** Sustainable intensification in peri-urban places

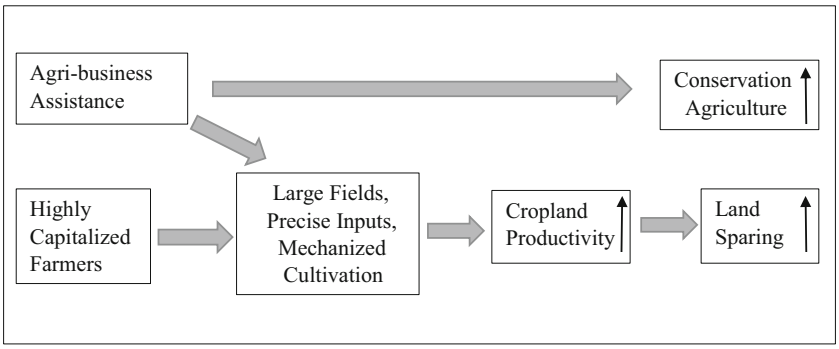


**Fig. 3** Sustainable intensification in large farm districts

Recent reviews of sustainable intensification in agriculture (Clark and Tilman 2017; Ramankutty et al. 2018) have emphasized the potential importance of dietary changes in fostering processes of sustainable intensification in the agricultural sector. While newly prosperous urban households in developing countries have increased their consumption of animal protein, appreciable numbers of urban consumers in long affluent societies began to consume more plants. Different survey research outlets have recently reported modest upticks of interest in plant-based diets. The percentage of Americans self-identifying as vegetarians in the quarterly food demand surveys in the USA has increased from 4.7% in May of 2013 to 8.8% in May of 2018 (http://www.agecon.okstate.edu/agecon_research.asp). In India, adherence to vegetarian diets increased from 25% in 2004 to 29% in 2014 of all respondents (http://censusindia.gov.in/Census_Data_2001/baseline/baseline2004.pdf; http://www.censusindia.gov.in/vital_statistics/BASELINE%20TABLES07062016.pdf, Table 5.1). News reports from China describe a recognizable pattern of increasing adherence to plant-based diets among young, urban dwellers at the same time that newly affluent, rural to urban migrants have increased their consumption of meat (https://www.news18.com/news/world/chinese-are-giving-up-on-meat-and-turning-vegetarian-heres-why-1672259.html).

Vegetarians seem to congregate in urban places in industrialized societies (MacKendrick 2018). Their growing presence in urban markets has inclined peri-urban producers to produce vegetarian foods for urban and peri-urban markets. These harvests usually reach consumers through supermarkets and farmers' markets. Farmers' markets tend to be located in or adjacent to urban areas.[1] The vendors at these markets accumulate relatively few food miles in getting their products to consumers. These short supply chains also minimize the spoilage of green leafy vegetables that farmers supply in large quantities to these markets (Vaarst et al. 2018). The relatively high prices for vegetables increase the incomes for these farmers (van den Berg, van Wijk, Van Hoi 2003). In effect, the emergence of these farmers' markets over the past two decades has begun to relocalize the food systems of people who patronize farmers' markets. The relocalization of the food system has enhanced the food security of consumers by increasing the numbers of nearby suppliers and reducing post-harvest food losses at the same time that it has increased the profits of small-scale agricultural producers near cities.

The emphasis on leafy produce in these markets has also facilitated a shift by urban consumers in affluent societies towards more plant-based diets. Smallholders from peri-urban zones seem to be enthusiastic participants in this change perhaps because they enjoy an additional economic advantage compared to other farmers. The mark-ups in the sale of agricultural commodities in peri-urban markets tend to be higher than in larger agricultural markets, perhaps because the demand for "quality" local products is less elastic than it is for conventionally cultivated crops in larger scale, conventional markets (Seufert and Ramankutty 2017).

Nutrients to feed these plants come increasingly from urban wastes. Farmers have long used manure to sustain agricultural production on their lands, but the cost of transporting the manure has limited this practice to land in villages and cities close to animal stalls and pastures (Liu 1999; Chisholm 1962). With rapid growth in urban populations and a commensurate growth in peri-urban agriculture, the volume of urban waste recycled as manure onto peri-urban fields has grown outside of cities like Bamako, Kumasi, and Ouagadougou in West Africa (Adam-Bradford, MacGregor, and Simon 2006; Eaton and Hilhorst 2003). The same dynamic appears to have taken hold in affluent regions like the Chicago metropolitan area in the mid-western USA (Lovell 2010). To be sure, these urban waste streams must be filtered to eliminate inorganic materials like plastics before farmers apply the wastes to land. The compost does, if consistently applied, accelerate nutrient recycling and restore the fertility of previously degraded soils in peri-urban zones.

The outward expansion of metropolitan areas generates several other streams of income for peri-urban farmers in affluent societies where they have secure titles to land. Landowners in these rural-urban fringe areas often break up

[1] (Source: U.S. Department of Agriculture, National Farmers' Market Directory. https://medium.com/@Esri/the-rapid-rise-of-farmers-markets-69c406b91a14).

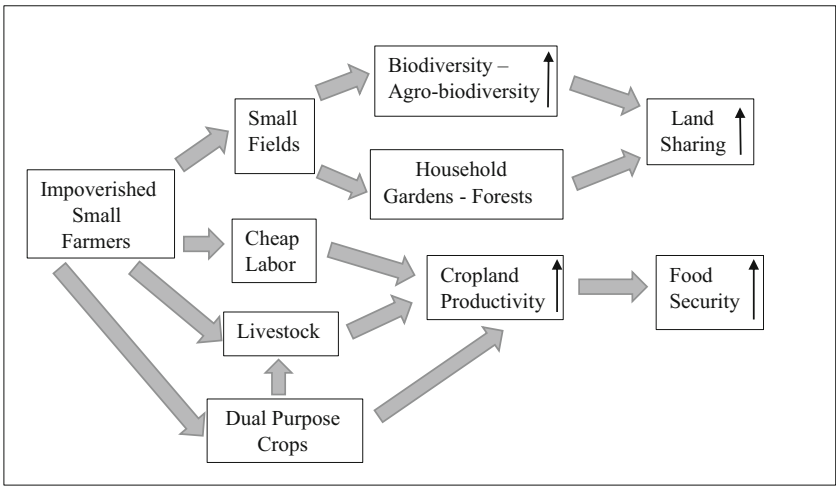


**Fig. 4** Sustainable intensification in small farm districts

their farms and develop the frontage along roads for urban uses like houses. These landowners often continue to cultivate the remainder of the farmland (Jarosz 2008; Rudel 1989). Because the value of farmland appreciates with the expansion of urban land uses out from the urban core, the sale of farmland for urban uses generates income for poor smallholders. This source of income is less available in more impoverished societies where squatter settlements proliferate in peri-urban zones. The growing proximity of urban labor markets opens up other economic opportunities for small farmers in both rich and poor societies. Their location near urban areas gives them access to large numbers of non-farm jobs that can provide additional income for their households (Lerner et al. 2013; Jarosz 2008).

The relative wealth of peri-urban farmers makes them more likely than other farmers to undertake productivity enhancing improvements like irrigation (Thebo et al. 2014). The proximity of peri-urban farmers to one another, accentuated by their routinized get-togethers in farmers' markets, also makes it more likely that they will organize into non-governmental organizations that promote their economic interests and encourage the adoption of new, sustainable intensification inducing technologies (Warner 2007; Kurgat et al. 2018).

Does the intensification of production in these peri-urban zones imply land abandonment and sparing in remote rural districts? In theory, "yes," but there are few empirical studies of this cause and effect. Recent patterns of land use change in Cuba, admittedly an unusual case, do suggest a contraction in agricultural lands far from cities and a corresponding increase in peri-urban and urban agriculture. With the decline of the Cuban sugar industry and the growth in urban horticultural pursuits following the collapse of the Soviet Union in 1991, land abandonment and sparing concentrated in the remote rural districts of Cuba (Álvarez-Berríos et al., 2013). Peri-urban zones around the city of Havana saw an expansion in agricultural production during this same period despite the difficult macro-economic conditions experienced by Cubans (Rudel 2019:105).

While the increased consumption of vegetables sold in peri-urban settings has been modest in terms of the entire food system, the growth in the numbers of these markets and their persistent emphasis on "high quality" foods suggests that the association of plant-based diets with peri-urban agriculture in affluent societies is not an ephemeral phenomenon. Rather, it is a persistent feature of a certain kind of urban focused sustainable intensification in agriculture (MacKendrick 2018; Bruce 2019). In effect, a synergy occurred between urban expansion, trends in consumer tastes, and the relocalization of agricultural production through the spread of farmers' markets. Together, these trends have increased peri-urban farm incomes, enhanced food security, and delivered some environmental benefits to society.

## More precise inputs in large farm agricultural districts

Industrial farming districts contain large farms located at an appreciable distance from cities (see Fig. 1). The distance from urban markets increases the food miles that agricultural products have to travel, but the long distances from city centers lower the price of cropland. The lower land prices in turn make it possible for families and firms to acquire extensive tracts of land and operate them as large farms. Over time, the assembly of these large, sometimes still family run farms enables their operators to pursue economies of scale and associated efficiencies in acquiring agricultural inputs. Sustainable intensification in these places would entail increased capital expenditures for new, more efficient inputs like irrigation systems, no-till planters, and genetically modified seeds (Foley et al. 2011). The gains in efficiency would come from the adoption of more precisely applied agricultural inputs like drip irrigation (Montpelier 2013). The pursuit of more efficiency in the use of inputs could also lead to a consolidation of farms

(Chisholm 1962). Farmers with fragmented landholdings would consolidate them, where possible, into contiguous blocks of land that could be cultivated with reduced expenditures of energy and labor. This reorganization of agricultural operations would contribute to gains in the efficiency with which farmers bring crops to market. This kind of consolidation occurred in western European agriculture during the decades immediately after World War II (Woodruffe 1989).

The owners of large farms have had relatively easy access to capital that they have used to make technological changes in agriculture. They might use newly developed tunnel greenhouses or irrigation systems to expand the number of crops harvested during a calendar year, from one to two crops or from two to three crops (Foley et al. 2011; Bruce et al. 2019). They might practice conservation agriculture, using no-till planters developed by agri-businesses to limit the amount of plowing on their lands. The reduction in plowing would reduce the farmers' fuel and labor costs. It would also reduce soil erosion (Coughenour and Chamala 2000). Conservation agriculture is not for all farmers. Impoverished smallholders in sub-Saharan Africa find it less attractive given the high cost of the new no-till implements and the uncertain returns in harvests (Pittelkow et al. 2015).

There is also little reason to expect increases in agro-biodiversity with the spread of sustainable intensification in industrial farming districts. Farmers in these districts choose, almost invariably, to cultivate the highest producing cereal crops, and they sell their harvests to international traders who, in turn, often sell these commodities as animal feed. The pursuit of economies of scale in these agricultural economies works against an agro-biodiverse set of cultivars. The frequent use of herbicides and pesticides impoverish the biota on cultivated lands and adjacent fields, so the biodiversity of large farm agricultural landscapes is lower than in smallholder-dominated, less chemically dependent landscapes (Riccairdi 2019). Large fields contain a relatively small proportion of their land along their more biodiverse edges, so large farms with large fields contain relatively low levels of biodiversity (Smith et al. 2020).

The large sums of money expended on the purchase of agricultural inputs in these districts attract corporate interest, so the agents of seed companies work with individual farmers and networks of farmers to raise the productivity of existing crops and promote the adoption of new crop varieties that resist damaging, profit-reducing blights (Warner 2007). These networks of farmers become vehicles for collective action that promote agro-ecologies which reduce the vulnerabilities of the cultivated plants, the surrounding biota, and the farmers that derive their livelihoods from these crops. These organizational dynamics promote rapid rates of innovation and the adoption of more efficient inputs (Kurgat et al. 2018). This pattern of investment would include an extension of irrigation systems throughout many industrial farming districts (Thebo et al. 2014).

The synergies that drive increased agricultural production in these large farm districts bring together large farms, ease of access to capital, assistance from corporations, scale economies, and new technologies like conservation agriculture. The interaction of these different elements contribute to higher levels of agricultural production, lower prices for agricultural commodities, and declines in the energy intensity of crops. Neighboring farmers see the intensification of production. They copy innovations from one another and expand the size of their farms. In this manner, innovators on large farms can induce nearby agricultural expansion and forest losses.

Recently, large farm districts have appeared suddenly when groups of investors have purchased large tracts of arable land in impoverished countries (Borras et al. 2011). The harvests from these newly purchased lands, which in developing countries may have, historically, gone to local residents, now get sold to consumers overseas who will pay more money for the crops. The redirection of these locally produced foods to overseas destinations compromises the food security of people living near the "grabbed lands" (Borras et al. 2011; Davis et al. 2015; Meyfroidt 2018).

This dynamic sounds, overall, like intensification without increments in sustainability or food security. There are, however, some extra-local, countervailing conservation tendencies. The same dynamic that contributes to agricultural expansion in industrial farming districts can contribute, as in the earlier discussion of trade-offs, to land sparing on lands in other parts of the world (Hertel et al. 2014). For example, a land sparing dynamic across different types of land has characterized northern Argentina during the past thirty years. Growers with access to substantial capital converted level, low elevation scrub lands into large soybean fields that they cultivated with machines. In the mountainous areas in the Andes to the west, smallholders abandoned small farms on accentuated terrain, and these spared lands reverted spontaneously to forests (Nanni and Grau 2014). Over time, this land sparing dynamic redistributed croplands to lowlands and forests to highlands (Wilson et al., 2017).

The twentieth-century cotton cultivation provides an example of large-scale land sparing across different regions of the world. The expansion of intensive cotton cultivation in the Nile delta of Egypt, beginning during the American Civil War and accelerating after World War II, induced the abandonment of long cultivated, eroded cotton fields in the American South (Fite 1984). Forests regenerated on these abandoned cotton lands during the 1950s and 1960s. This sparing of lands in marginal agricultural zones, along with the increased efficiencies of inputs, less invasive cultivation techniques, and large harvests of staples, contributes, together, to the synergies that drive large farm focused sustainable

intensification. Fig. 3 outlines the dynamics of sustainable intensification in large farm districts.

## Land sharing in smallholder districts

Despite their small size, averaging less than 2 ha per farm in many districts, smallholder, mixed crop-livestock farms produce about one-half of the world's food (Herrero et al. 2010), so sustainable intensification on these farms represents an important component in any global strategy. Place-based obstacles to change, in particular the poverty of the cultivators and the often uneven topography, shape the particular kind of sustainable intensification practiced in smallholder-dominated agricultural districts far from cities.

Small fields and mixed crop-livestock operations foster sustainable intensification in these settings. The small fields have greater edge to area ratios compared to large fields. The edges promote both biodiversity and agro-biodiversity by providing varied plant cover (Smith et al. 2020). Commercial crops and other non-crop plant assemblages often share small fields and spaces in these landscapes. Understory crops like coffee and rubber grow beneath trees whose litter maintains the fertility of the soils (Pearce 2018).

Land sharing regimes have also appeared in small-scale cattle ranching regions in South America where pastures have evolved into silvo-pastures. With the spontaneous germination of trees in pastures, the trees, the cattle, and the shade-tolerant pasture grasses have come to share the same fields. The production of cattle has not diminished. The biodiversity in pastures has grown, and the sale of wood from the trees in pastures has provided the small-scale cattle ranchers with an additional source of income (Lerner et al. 2015). While the extent of land sharing through shifting cultivation may have diminished, at least in the uplands of southeast Asia, during the past fifty years (Van Vliet et al. 2012), land sharing through silvo-pastures in the Amazon basin appears to be increasing in extent (Lerner et al. 2015).

Mixed crop-livestock farms predominate in many smallholder regions, and these operations promote synergies between crop cultivation and animal husbandry. Livestock turn the earth in preparing for planting, and they provide manures to fertilize the fields. When farmers do apply manures, they only transport them short distances, from a stall in a barn to a nearby field (Liu 1999). Crops serve a dual purpose in this agro-ecology. They provide grain for human consumption, and their residues in the fields provide fodder for livestock (Herrero et al. 2010). Plant breeding advances in crops like millet and sorghum have improved the quality and quantity of crop residues with corresponding improvements in livestock. Continued progress in the breeding of these dual purpose crops would appear to be an important component in any sustainable intensification program among smallholders. Advances in this domain would also bolster the food security of poor families given the proximity of fields to kitchens in nearby villages. The low cost of labor on most small farms also makes it easier for smallholders to market crops at low prices to local residents and, in so doing, enhance the food security of local populations.

While the harvests of some crops like potatoes from smallholder districts follow short supply chains from fields to markets in nearby villages, harvests of some non-essential, high value crops like coffee become part of long supply chains that extend from small fields in remote rural settings to supermarkets in wealthy urban areas. Fair trade arrangements and smallholder entry into distant but high priced consumer food markets represent a viable path to sustainable intensification for some impoverished, environmentally degraded smallholder districts (Lyon 2011; Rueda and Lambin 2013). Taken together, the land sharing arrangements promote biodiversity in these heavily cultivated landscapes at the same time that mixed crop-livestock farms practice a highly productive, albeit small in scale, agriculture that enhances the food security of rural peoples.

Any emerging pattern of sustainable intensification in these rural, smallholder districts has to work around several formidable obstacles to change. First, smallholders in these settings belong to few non-governmental organizations that might put them in touch with extension agents who could help smallholders acquire more efficient technologies (Reardon et al. 2009). Second, the poverty of these smallholders and a corresponding lack of access to credit begins to explain why they have often been reluctant to adopt new, more efficient agricultural technologies (Cancian 1979; Kurgat et al. 2018). Fig. 4 outlines the forces that shape sustainable intensification in smallholder districts.

While land sharing landscapes predominate in rural smallholder districts, land sparing sometimes occurs in contiguous agro-ecological zones. Rural to urban migration from smallholder agricultural districts has contributed to declines in the numbers of smallholders and declines in the extent of land-shared, smallholder-cultivated areas in rural districts (Grau and Aide 2007). The out-migration and declines in smallholder-cultivated areas spare some lands. The land sparing occurs on a larger national or continental scale, while land sharing occurs at smaller scales in the smallholder-dominated rural districts embedded in a large farm agro-ecology (Fischer et al. 2014). In this respect, land sparing and land sharing are not mutually exclusive sustainable intensification dynamics. They can co-exist, albeit at different geographical scales, in the same larger region. Land sharing on small farms occurs alongside land sparing in highlands triggered by out-migration and agricultural intensification in distant, lowland industrial farming districts.

## Conclusion: Sustainable intensification strategies and government initiatives

The three paths to sustainable intensification described here do not deliver the same magnitude of benefits. Studies have shown, for example, that land sparing spurred by productivity gains in industrial farming districts produces a larger magnitude of environmental gains than land sharing in smallholder districts (Phalan et al. 2011). A still larger magnitude of gains from sustainable intensification might be achievable through a strategy that acknowledges differences in socio-ecological conditions across agricultural districts and adjusts the sustainable intensification strategy accordingly. One strategy, focused on vegetarian inclined consumers and farmers' markets, would apply in peri-urban zones. Land sparing would be promoted in large-scale farming districts, and land sharing would be encouraged in small-scale farming districts. The different dynamics in each region indicate that sustainable intensification entails different sets of changes in each region.

All three of the sustainable intensification initiatives described above have occurred against a backdrop of government passivity. Governments have, by and large, failed to mount large-scale efforts to promote sustainable intensification in agriculture. To be sure, institutions dedicated to agricultural improvements like the CGIAR (Consultative Group for International Agricultural Research) centers have endorsed sustainable agricultural intensification (Blomqvist 2015), but national governments have not launched large-scale efforts to foment it. In this context of government inaction, situational variables, like proximity to urban centers and the size of farms, have contributed to the synergies that have, to date, marked successful efforts at sustainable intensification in agriculture.

Given this history, the success of government interventions to promote sustainable intensification would seem to depend on the ability of program leaders to take advantage of place-specific synergies. Kaimowitz (2002) characterized these place-based strategies of intervention with the following words:

> "To succeed, strategies should capitalize on the trends that are already
> driving the economy and people's decisions [in a place] and nudge them in the right
> direction…"

A focus on creating government programs to enhance place-based synergies, as outlined in the Kaimowitz quote, promises to produce sustainable intensification without triggering countervailing trends or trade-offs. Promotions of peri-urban agriculture, through farmers' markets, promise an expansion in plant-based diets with their benign environmental effects. Conservation agriculture, implemented with new precision technologies to foster plant growth, builds on synergies exploited by agri-businesses in the large farm sector. Finally, more concerted efforts by governments to promote mixed crop-livestock agriculture in rural, small farm districts promise to boost agro-biodiversity and food security among the world's most impoverished farmers. In this manner, each set of government programs would build on pre-existing trends in particular agricultural sectors to increase the magnitude of the economic and environmental gains in local trajectories of sustainable intensification in agriculture.

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