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# Food security and biodiversity: can we have both? An agroecological analysis

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**Abstract** We present an extensive literature review exploring the relationships between food insecurity and rapid biodiversity loss, and the competing methods proposed to address each of these serious problems. Given a large and growing human population, the persistence of widespread malnutrition, and the direct and significant threats the expanding agricultural system poses to biodiversity, the goals of providing universal food security and protecting biodiversity seem incompatible. Examining the literature shows that the current agricultural system already provides sufficient food on a worldwide basis, but in doing so methodically undermines the capacity of agroecosystems to preserve biodiversity. However, the available evidence emphasizes the interdependence of biodiversity and agriculture, and the important role each plays in the maintenance of the other. Thus, our review supports the claim that the solutions to the problems of widespread food insecurity and biodiversity loss need not be mutually exclusive, and that it may be possible to address both using appropriate alternative agricultural practices.

**Keywords** Agroecology · Alternative agriculture · Biodiversity · Conservation · Food security · Organic agriculture · Political ecology

**Abbreviations**

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| ADA | American Dietetic Association |
| CNPP | Center for Nutrition Policy and Promotion |
| FAO | Food and Agriculture Organization of the United Nations |
| GM | Genetically modified |
| IAASTD | International Assessment of Agricultural Knowledge, Science, and Technology for Development |
| IPM | Integrated pest management |
| IPNS | Integrated plant nutrient systems |
| NRC | National Research Council |
| SMAB | Secretaria Municipal de Abastecimento |
| UNCCD | United Nations Convention to Combat Desertification |
| UNDP | United Nations Development Programme |
| UNMP | United Nations Millennium Project |
| WHO | World Health Organization |

## Introduction

Among the challenges facing the world today, the urgency of providing food security[1] to the growing human population and slowing the rapid loss of irreplaceable biological

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[1] The definition of food security used here and in the rest of this work is: physical and economic access by all people in a society at all times to enough culturally and nutritionally appropriate food for a healthy and active lifestyle (FAO 1996). Under this definition, obesity and hunger are equally considered to be problems of food security. Both are related in great part to the structures of government subsidies, global trade, narrowing of the food base, inequality, poverty, and lack of food sovereignty. And it may be possible to address both to a great extent by changing the focus of agricultural production to a food system focused on substantive equality, local production, biodiversity, and dietary diversity (Frison et al. 2006; Friel et al. 2007). Insofar as these issues converge, obesity will be (indirectly) addressed in the present work; but the primary focus will be on the hunger and nutritional insufficiency aspects of food security.

diversity loom large. A sense of urgency is warranted in both cases: estimates of the current rate of loss of biodiversity range from several hundred times the background (i.e., “natural”) rate (Pimm et al. 1995) to between 1,000 and 10,000 times the background rate (Hanski et al. 1995; but see Ibáñez et al. 2006), and approximately *one billion* people are malnourished today (FAO 2008). Indeed, the loss of biodiversity is likely still accelerating (Gaston and Fuller 2007), with 1–10% of the world’s species projected to be lost in the next quarter century, a rate comparable to the Cretaceous extinction event that marked the demise of the dinosaurs (Hanski et al. 1995; Lawton and May 1995; Alroy 2008). The commitment made by 182 countries at the 2002 World Food Summit to halve the number of malnourished people by the year 2015 to approximately 425 million people has recently been made “much more challenging” in the words of the FAO: since 2006, spikes in food prices have effectively wiped out and partially overtaken previous gains in decreasing malnutrition worldwide (UNMP 2005; FAO 2006, 2008). In reality, food prices have increased due to a number of factors, including market volatility, increased petroleum prices, and biofuel demand, increasing the number of malnourished in many, if not most countries (FAO 2006, 2008; IAASTD 2009). Worse, these measures do not even address the more than two billion people thought to be suffering from undernourishment in the form of dietary imbalances or specific nutrient deficiencies throughout the world (UNMP 2005; WHO 1996).

The two problems of biodiversity loss and food insecurity are global in scope and cannot be viewed independently: in a world with limited resources the methods used to address one necessarily involve choices affecting the other. Human beings consume between one-tenth and one-half of the planet’s net terrestrial food supply in terms of photosynthetic production (Vitousek et al. 1997; Rojstaczer et al. 2001; Krausmann et al. 2007). Approximately 40% of the earth’s land surface is being used for agriculture; an estimated 16–40% of this land is already lightly to severely degraded. Current human use of surface water is likely unsustainable, and our uses of both soil and groundwater almost certainly are, as they are essentially non-renewable resources (Hillel 1991; Ehrlich et al. 1993; Vitousek et al. 1997). Such uses of significant amounts of the world’s resources necessarily carry profound consequences for the world’s ecosystems and their ability to support biodiversity.

Thus Malthus’s dictum that a growing population will inevitably exceed its environment’s limited capacity to produce food, despite ignoring a number of important complexities, contains an undeniable truth: an ever-increasing population will inevitably overtax its resource base in a finite world (Malthus 1798; Arrow et al. 1995; Vandermeer 1996). As Malthus’s many intellectual inheritors have pointed out, starvation is just one of the consequences of a large and ever-growing population. Although predictions of a population peak at or under 10 billion people by the year 2100 have been shown to be relatively robust (Lutz et al. 2001; O’Neill 2005), it has been proposed that the world cannot sustainably support more than 2 or 3 billion people, carrying grave implications for earth’s biodiversity (Daly 1996; Wackernagel and Rees 1996; Pimentel et al. 1999; Smail 2003). Many researchers have concluded that the only or best way to meet these challenges is to produce more food with less land (i.e., agricultural intensification), likely coupled with population control and reduction (Ehrlich et al. 1993; Budiansky 2002; Fresco 2003; Balmford et al. 2005). Meanwhile, alternative analyses place much greater emphasis on factors that complicate sustainable universal food security, such as poverty, gender inequity, racism, and lack of political will, all factors that may prevent access to food. Proponents of such analyses generally advocate holistic, integrative, and regenerative approaches to sustainability over agricultural intensification per se; and propose that political change, equity, decentralization, land reform, or democratization are required to provide universal food security and preserve biodiversity—maintaining that intensification and population reduction themselves are problematic, and wholly inadequate or incomplete solutions (see Drèze and Sen 1989; Dahlberg 1993; Sen 1994; Lappé et al. 1998; ADA 2003; IAASTD 2009; Vandermeer et al. 2008). Before we delve deeper into such analyses, we must first understand how food security and biodiversity are related to each other.

Given the above, it appears that food security and biodiversity conservation cannot reasonably be addressed independently, giving rise to two broad alternatives:

1) The goals of food security for the present and future population and conservation of earth’s endangered biodiversity are inevitably contradictory, or
2) The two goals can be achieved with complementary means.

We intentionally avoid a number of important complexities in order to address elemental questions of feasibility, questions as vital as those regarding implementation and societal change. It is also important to note that this work deals mostly with agricultural production, as distinct from food systems: the commercialization, consumption, disposal, politics, and institutions of food are all areas that will need to be (re)designed at local, regional, and global scales, as well as at temporal scales (e.g., to compensate for seasonal food, climate variation, etc.) in order for food systems to be truly sustainable (Lowrance et al. 1986; Dahlberg 1993; Murray and Sánchez-Choy 2001; IAASTD 2009). Thus, our conclusions in this work will in reality indicate conditions or methods necessary, but not sufficient, to facilitate food security and conservation within a context of agricultural production. The aim of this review paper is, in a general sense, to evaluate minimum theoretical and technical feasibility, rather than to develop a specific roadmap to the future in terms of agriculture and biodiversity.

In terms of the structure of the paper, our analysis starts with State of the Biosphere: Global Food Security, an overview of the current state of global food security along with a review of two different broadly defined approaches to agriculture ("alternative" vs. "conventional"). The following section, State of the Biosphere: Global Biodiversity conducts a brief examination of the different types and definitions of biodiversity, the estimates of total global biodiversity, and how agricultural land use is related to biodiversity loss. The third section, Alternative Production, follows up on this by attempting to address the questions of whether alternative agriculture can provide enough food for the world population, and whether it can generally be said to better sustain biodiversity than conventional agriculture. A fourth section, State of the State: Regional Food Security and Biodiversity, examines our findings from a regional perspective and briefly presents several case studies to illustrate. Lastly, Conclusions reviews and expands on the synthesis of the literature presented; and answers the question of whether, based on the synthesis, one of the above alternative claims about food security and biodiversity's compatibility can be supported.

## State of the biosphere: global measures of food security

While global food security is wholly insufficient to guarantee food security at other scales (i.e., on a national, local, or individual basis), it is nonetheless an important prerequisite. The inability to generate sufficient food globally necessarily means that some or all regions of the world suffer from food insecurity. Therefore, our analysis starts with global food security before addressing the more complex issue of regional food security.

Current food production systems encompass the spectrum from industrialized high-input, high-yielding practices to traditional indigenous agricultural systems that have been developed over thousands of years (Altieri 1990; Netting 1993; Rosset 1999; Bruinsma 2003). At one end, conventional practices include a dramatic reduction of biodiversity to allow specialization in fewer high-input crops, encouraging and resting on (a) an industrial model of increased production centralization/consolidation; alongside (b) functional separation; (c) claims of economic efficiency; (d) and attempts to control and manage nature as just another commodity (Matson et al. 1997; Vandermeer and Perfecto 1997; Evenson and Gollin 2003). The inputs in conventional intensive agriculture—also called industrial agriculture—are synthetic fertilizers and pesticides, usually produced with the heavy use of fossil fuels, applied in order to subsidize the continual extraction of soil nutrients in the first case, and to reduce yield loss from competition and herbivory in the second (Tinker 1997; Buttel 1990). Along with a high degree of mechanization (again involving heavy fossil fuel use) and irrigation, these practices characterize the endpoint of much of modern agriculture (Dahlberg 1993; Giller et al. 1997; Izac and Sanchez 2001; IAASTD 2009), although the actual degree of adoption of each practice varies enormously. At the other end of the agricultural spectrum is the broad category of alternative agriculture, which ranges from traditional indigenous practices to the US organic system codified in 2002. More than a dozen terms have been used for these closely related methods, including "low-input," "sustainable," "ecological," "agroecological," "biological," and "organic" agriculture (Pinstrup-Andersen 2003); and "integrated pest management" (IPM), "integrated plant nutrient systems" (IPNS), and "no-till/conservation agriculture" (NT/CA) (Merrill 1983; Lockeretz 1989; Vandermeer 1995; Bruinsma 2003).[2] In general, alternative approaches look to create or maintain a more holistic and multifunctional system, involving and integrating natural ecological processes as much as possible; using high levels of recycling; and recognizing the fundamental interconnections between agriculture, human culture, and larger social issues in the rest of the food system (Dahlberg 1993; Pretty 2002; IAASTD 2009). The National Research Council (NRC) (1989), rather than characterizing alternative agriculture as a certain methodology, defined it as a range of management and technological options used to reduce costs, protect health and the environment, and enhance biological interactions and natural processes, similar to Lockeretz's (1991) and Bruinsma's (2003) evaluations of alternative practices as complementary methods targeted at improving sustainability. The methodological differences between alternative and conventional agriculture include: lowering or eliminating pesticide use, elimination of mechanization where practical, and lowering or eliminating inorganic fertilizer use (all of which also decrease reliance on fossil fuels). Reduced external and inorganic inputs are replaced by

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[2] One newer component increasingly included in this list is a specific call for locally-focused food systems, such as the "nearness principle" of the Danish Research Centre for Organic Farming (2000). Locally-based food systems may cut down on resource consumption and pollution produced by the long-distance transportation of foodstuffs and agricultural inputs, and also may increase transparency and reduce alienation between producer and consumer by facilitating direct contact between these groups (Heller and Keoleian 2000; Pretty et al. 2005). (See also Note 25.).

various natural ecosystem processes, including: lengthened fallow periods and use of green manures, crop rotations, intercropping, greater crop and animal diversity, and natural predators as pest control. As with conventional agriculture some, all, or none of these practices may be used in any given system.

A general assessment of production methods shows that small farms using alternative agricultural techniques may be two to four times more energy efficient than large conventional farms; total energy output/input ratios from alternative systems may range from 11:1 (corn) to 1:20 (beef), while modern/conventional systems may see ratios from 2.5:1 (corn) to 1:40 (beef) (Pimentel and Pimentel 1996; Pimentel 2006). The lower energy-efficiency of conventional systems is due to high inputs of synthetic chemicals (fertilizers, pesticides), use of pumped water, fuel for on-farm machinery, and production and shipping of external inputs (Heller and Keoleian 2000).[3] However, agricultural production itself accounts for only about 20% of the total energy consumed in the US food system. Minimizing energy used to process, package, distribute, and prepare food therefore represents an opportunity to decrease off-farm energy use. As fuel prices increase and global climate change continues, the benefits of more energy-efficient diets will only become more significant (Pelletier et al. 2008).

Nonetheless, the use of conventional agriculture has grown rapidly since the 1950s and today dominates the world system in terms of land area (Evenson and Gollin 2003), while organic agriculture today accounts for approximately 0.7% (30 million ha) of agricultural land in the world (Willer and Yussefi 2007, based directly on data from 123 countries).[4] The additional 62 million hectares of registered areas with "organic wild collection" could also be considered to be under alternative agricultural management; they occupy a total area equal in size to 1.4% of global agricultural land (Willer and Yussefi 2007). The use of conventional inputs on the ~98% of land where alternative practices are not used has grown to such an extent that fertilizer applications have been estimated to account for 43% of the nutrients that global crop production extracts each year (Fresco 2003). Assuming further intensification, Fresco estimated that fertilizer application might account for up to 84% of nutrients extracted in the future—virtually turning the world's soil into a hydroponic medium. So can this current and future regime of intensive agriculture provide enough food to feed the world?

As we mentioned in the Background section, many researchers have long assumed that population growth is a primary cause of food insecurity, and correspondingly advocate increasing intensification of agriculture as a partial solution. However, many contend that population size, food availability, and food security have a more complex relationship than Malthusian principles would have it. This is immediately apparent: Despite population growth since 1961, per capita food availability for the world increased by 24% in the same period (Bruinsma 2003; FAO 2007). Today, worldwide, close to 2,800 calories per person per day are available, yet 1 billion persons are malnourished even though the recommended daily intake of calories is approximately 2,200 calories (CNPP 2000; FAO/WHO/UNU 1985). Further, data from the early 1990s showed that nearly 80% of all malnourished children in the developing world lived in countries reporting food surpluses (Bruinsma 2003; Gardner and Halweil 2000).

It is nonetheless widely thought that, given a projected human population of 9–10 billion people, it will be necessary to both expand agricultural land use and intensify agricultural production in order to provide food security in the future. In regards to intensifying production, the use of genetically modified (GM) crops is often suggested to mitigate such expansion's encroachment into biodiversity-rich areas by supposedly maximizing intensification on existing land (Trewavas 2002; Fresco 2003; Balmford et al. 2005). However, a number of factors cast doubt on GM crops' potential to aid global food security: GM crops have mainly benefited large farms and multinational companies rather than delivering promised benefits for poor and small farmers (Monastra and Rossi 2003; García González 2007; Uphoff 2007; Verhoog 2007; but see Herring 2007); studies of health risks to humans and animals have been contradictory and controversial (see for example Ewen and Pusztai 1999; Freese and Schubert 2004; Wilson et al. 2004; Malatesta et al. 2005; Filipecki and Malepszy 2006; Semal 2006; Séralini et al. 2007; but see Brake et al. 2004; Sanden et al. 2006; Doull et al. 2007; Larkin and Harrigan 2007); and although the occurrence of any negative environmental effects has not been established in the literature (Sanvido et al. 2007), many researchers point out that

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[3] Alternative systems may also have lower run-off of nutrients than conventional systems, meaning in turn higher resource use efficiency (see Note 23). This use efficiency further means that less energy is used to recover, produce, transport, and apply nutrients.

[4] The stated percentage (0.7%) is potentially an underestimate. Willer and Yussefi specifically note that their data only cover 63% of all countries. Additionally, home and urban gardens, subsistence agriculture and other parts of the "informal economy," as well as uncertified de facto organic systems constitute an unknown quantity of additional land under alternative agriculture. Such systems are often nearly invisible or overlooked in large surveys, including the country-wide surveys of organizations like the FAO (pers. obs.; Young 1999; Pretty and Hine 2001; Greene and Kremen 2003; Pretty et al. 2003; Willer and Yussefi 2007). The recent negative economic climate has highlighted the potential and growing importance of informal and small-scale efforts, such as organic urban and community gardens, to significantly contribute to local food security, equity, and sustainability (Smit and Nasr 1992; National Gardening Association 2009). However, the significance and size of these efforts are poorly studied, and have been called into question by some researchers (Ellis and Sumberg 1998).

serious ecological threats remain (Lewis and Kareiva 1993; Tomov and Bernal 2003; Saito and Miyata 2005; Shirai 2007; Letourneau et al. personal communication). Such ongoing debates provide compelling reasons to embrace the precautionary principle in regards to GM crops, making them a potentially poor tool for increasing intensification.[5] With or without GM crops, it seems likely that agricultural land will continue to expand and encroach further into tropical forests and other biodiverse areas (Angelsen 1999; Angelsen and Kaimowitz 2001; de Sherbinin et al. 2007; Sloan 2007).[6] Based on assumptions of increases in agricultural land base and yield per unit area, FAO projections indicate that, in 2020, approximately 2,900 calories per capita per day will be available in the developing world (and about 3,480 calories in industrialized countries); and that in 2050, when the human population is projected to reach 8.9 billion, 3,070 calories will be available in the developing world (with about 3,540 calories in the industrialized countries) (Alexandratos et al. 2006). The assumed increase in agricultural land to produce such numbers is 25–28%, although it is estimated that upwards of 75–90% of the land suitable for agriculture is already in use (Young 1999; Sloan 2007). Meanwhile, the argument that intensifying agricultural land use (usually with conventional means, sometimes including GM crops) to produce more food on less land will "save" extra land for biodiversity (see Tilman et al. 2002; Balmford et al. 2005; Fischer et al. 2008) may not itself be valid, beyond the fact that it ignores the effects of agricultural matrices on adjacent natural habitats (see Dorrough et al. 2007; Perfecto and Vandermeer 2008; Chappell et al. 2009). In two works reviewing theoretical approaches and a number of empirical case studies, Angelsen and Kaimowitz (1999, 2001) determined that intensification—increasing yields per unit labor or unit capital—can strongly encourage greater deforestation. The basic explanatory mechanism is rooted in elementary economics and illustrates the dangers of an analysis that does not look beyond a technical production context. An increase in labor or capital efficiency encourages in-migration of new agriculturalists and encourages farmers to *increase* forest clearing, due to the fundamental economic pressure to take advantage of successful high-yielding practices. In contrast, intensification that increases yields per unit area, but requires more labor, was found to generally avoid spurring in-migration and expansion. Therefore, if the discussion is about "saving land" for biodiversity, maximizing productivity per unit land area would be preferable to labor efficiency, and maximizing land productivity with increased labor would therefore presumptively do more to avoid agricultural land expansion. It also would have the potential to lessen rural unemployment and urban in-migration from the countryside in many areas of the developing world (Rocha and Aranha 2003; Badgley et al. 2007).[7]

Strictly with respect to food security, it is not even clear that more land is necessary to produce sufficient yields to adequately feed the world (making the "saving land for nature" argument superfluous). Indeed, a recent study by Badgley et al. (2007) implies that intensification in developing countries using alternative *or* conventional methods may be able to increase production on the current land base sufficient to provide enough food on an average caloric basis for a world population of even 10 billion people. Looking at 293 examples comparing alternative and conventional agriculture from 91 studies from varying locations, conditions, and approaches, they concluded that the literature to date supports the finding that even under conservative estimates, alternative agriculture could on average provide almost as much food (on a caloric basis) at the global level as is produced today (2,641 as opposed to 2,786 kilocalories/person/day after losses). In their so-called more "realistic" estimation, alternative agriculture could actually increase global food production by as much as 50% (to 4,381 kilocalories/person/day).[8] Note that the

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[5] Briefly summarized, the precautionary principle indicates that when there are reasonable grounds to suspect that new procedures and technologies may pose the risk of serious, irreversible, or widespread harm to public or environmental health or sustainability, they should be tightly regulated or wholly prohibited, regardless of a lack of full scientific certainty of the likelihood, magnitude, or causation of such harm, until it can be affirmatively shown that the new technology poses little or no significant risk.

[6] Increasing demand for biofuels is predicted to also contribute significantly to continued deforestation and biodiversity loss. In addition to direct negative effects on biodiversity, the rise of biofuels may form positive feedbacks with global climate change, forest dieback, and continued agricultural expansion, all of which in turn can contribute to further deforestation and biodiversity loss (Sawyer 2008; Searchinger and Houghton 2008).

[7] It is important to note that the most impressive advances in intensified conventional agriculture have been in increasing yield per unit labor (by 120 times, or about 45 times if one counts indirect labor costs) by replacing it with less energy-efficient subsidies (e.g., mechanization, synthetic pesticides and fertilizers). In contrast, alternative agricultural methods usually use increased labor inputs to increase yield per unit area (Pimentel and Dazhong 1990).

[8] Of course, sufficient global or even regional yields are not enough to guarantee food security in its full sense, as outlined in Note 1, because having enough food in an area does not guarantee equity of access or distribution such that adequate food is available to everyone in a society. Overwhelmingly, widespread hunger has been linked to poverty, political or structural problems, and other exigencies, and seems to only rarely occur due to an actual acute lack of food availability (Sen 1984; Patnaik 1991). This necessarily means that sufficient yields from any production method will not and often cannot provide food security in and of themselves, though sufficient yield is by definition a prerequisite. This is discussed briefly in the Conclusions, but as has been noted throughout, the larger context of food systems and food institutions is important but beyond the scope of the present work.

claim is not that alternative agriculture can necessarily produce higher yields than conventional—just that it can provide sufficient yields for food security. Though such results may appear surprising, the "realistic" scenario reflects the fact that many farmers in poorer nations use low-intensity methods (subsistence farming or other non-industrialized methods) and may not ever have adopted conventional agricultural technology. Badgley et al.'s study also looked at the production of organically acceptable nitrogen sources and found, based on 77 studies, that no additional land would be needed to produce sufficient nitrogen to provide these yields. Thus, in principle, intensification to increase yields to higher levels could proceed using alternative or conventional methods, without more land; the argument that it may only be done with conventional agriculture does not fit the balance of evidence. Additionally, because alternative agricultural methods tend to be labor-intensive, they potentially negate the economic pressures for expansion elaborated by Angelsen and Kaimowitz. If it is therefore possible for alternative agriculture to provide sufficient yields, maintain a higher level of biodiversity, and avoid pressure to expand the agricultural land base, it would indicate that the best solution to both food security and biodiversity problems would be widespread conversion to alternative practices.

The evidence reviewed thus far therefore suggests that *global* food security is already hypothetically possible, and is plausible even for a larger future population. The implication is then that, on a caloric basis at least, the problem of food insecurity is a matter not of total availability but indeed one of access, political power, and equity. The fact that sufficient food supply is often available even in areas suffering from famines or persistent malnourishment belies the idea that today's billions of food-insecure people are a result of insufficient food production, leading the FAO, among many others, to argue that poverty is the major cause of malnutrition (Drèze and Sen 1989; Patnaik 1991; FAO 2002, 2006; ADA 2003). The problem of food security is not one of global supply then, but of a need for equitable global distribution and local accessibility, which implies that further conventional agricultural intensification is unneeded in the short, and possibly long, term.[9] Additionally, with severe on-farm decreases in biological diversity occurring as a result of modern industrial agriculture's focus on monocultures, simplification, and specialization, conventional intensification may not only be unneeded for food security, but also directly antithetical to biodiversity.

## State of the biosphere: global biodiversity

Biodiversity, like food security, is a regional as well as global property, and it can be divided into a number of interdependent levels. Such levels include genetic diversity, species and subspecies diversity, diversity of functional traits, diversity between populations or communities of species, ecosystems or habitat diversity, diversity among large landscape zones, and global diversity (Bisby 1995; Swift et al. 2004; Hooper et al. 2005). For the purpose of this review, biodiversity can be assessed globally to the extent that the rate of global loss represents a composite of the rates of regional loss—taking into account that extinction of unique or indigenous biodiversity represents its global loss by definition. At the core of all biodiversity concepts is the recognition that there are measurable, semi-regular, and classifiable variations between organisms and ecosystems at a variety of scales, and that when the ultimate source of such variation is wiped out, a unique form of being or place may be forever lost.[10]

Given the scope and complexities involved, exact estimates of biodiversity loss are difficult at best, making estimation of the species lost solely due to agriculture or population expansion more difficult yet. Today, there are an estimated 13 million species in the world, though estimates range from 3 million to 111 million. As outlined earlier, the current rate of extinction is potentially thousands of times higher than the rate estimated for most of evolutionary history, and is only increasing (Lawton and May 1995; Gaston and Fuller 2007). Based on studies of prior global extinction events, Alroy (2008) estimated that if similar levels of extinction are seen (from 32 to 81% losses of global biodiversity), it may take between 10 and 40 million years for biodiversity levels to recover. Such

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[9] This is further emphasized by the fact that the numbers do not take into account waste in the food system. Food waste from retailers, consumers, and food service in the US may make up as much as 27% of the total food supply. On-farm losses—including losses due to increasing mechanization—mean that the total proportion of waste is higher still. It is unknown how much of these losses are recoverable, but even low levels of recovery in the US would potentially feed tens of thousands of people a year (Kantor et al. 1997). If food waste in other countries is on the same order of magnitude, waste recovery efforts could potentially feed millions of people.

[10] Dahlberg (1993) points out that genetic and biological diversity undergirds all of the functional resiliency and regeneration of living systems, upon which the subset of *human* systems are dependent for survival. In this way, biodiversity has primacy over simple resources (renewable and non-renewable). This is further reinforced by the non-substitutability of many biological systems and resources; that is, *contra* classic economic theory, many natural resources cannot be substituted by increased use of an alternative but rather are unique and irreplaceable. Dahlberg likens this to the loss of one or two letters of the alphabet and the words that contain them, and the difficulties in language that would result. Such non-substitutability applies to many crucial elements of production agriculture, especially biodiversity, and is a basic principle of the field of ecological economics; see e.g., Prugh et al. (2000) and Daly (1996) in addition to Dahlberg.

numbers are clearly a reason for pause: Beyond intrinsic and fundamental cultural values offered by the diversity of earth's lifeforms, natural and biodiverse systems offer a number of other ecosystem services, including erosion control, groundwater and nutrient retention, carbon sequestration, pollination, pest control, nutrient recycling, climate regulation, flood and drought mitigation, air and water remediation, aesthetic values, recreation and leisure (Daily 1997; Prugh et al. 2000; Hooper et al. 2005).

There are a number of threats to biodiversity posed directly by human activities, principal among them being direct over-exploitation of organisms, environmental toxification, climate change, biological invasions, and habitat destruction and degradation (Ehrlich and Pringle 2008). Direct over-exploitation, from hunting and fishing to trapping animals for pets, can decimate the target species and can threaten to destabilize whole ecosystems in some cases. In terms of toxification, human activities release a number of byproducts that negatively affect biodiversity: for example, there are presently more than 400 reported dead zones—aquatic areas incapable of supporting life that can be generated or exacerbated by fertilizer run-off—covering more than 245,000 km$^2$ across the globe (Diaz and Rosenberg 2008). Pesticides and pharmaceuticals can also decimate non-target biodiversity (Ehrlich and Pringle 2008). Anthropogenic climate change can precipitate the extinctions of a number of organisms through a variety of mechanisms, such as changes to ocean temperature and pH causing the reduction and disruption of the megabiodiverse coral reef systems (the "tropical rainforests of the ocean"). The increasingly globalized world offers increasing chances of the introduction of invasive species, which can alter native ecosystems through predation, competition, and the disruption of co-evolved interactions, leading to decreased biodiversity and increased biological homogenization (Ehrlich and Pringle 2008). And of all the five previously mentioned factors, habitat loss and degradation may be the most significant cause of the accelerating rate of extinctions (Hanski et al. 1995). Human land use has rapidly expanded in the past several decades, converting natural habitats into cities and agricultural areas, logging biodiverse forested areas, directly exploiting biodiversity, polluting surrounding ecosystems, producing greenhouse gases, and introducing invasive species to new habitats in the process. Indeed, all five factors can generate positive feedbacks among themselves, reinforcing the damage each causes.

## Agriculture and biodiversity loss

Agriculture, occupying approximately 40% of the world's land surface (excluding Antarctica), represents perhaps the biggest challenge to biodiversity, directly in terms of the conversion/destruction of natural habitat for agriculture as well as the environmental effects of intensification, such as toxification from pesticides and fertilizers and generation of greenhouse gases from fossil fuel use (Bruinsma 2003; FAO 2007; IAASTD 2009). In comparison, in terms of land use alone, the global network of protected wildlife areas is estimated to cover 12% of the global land area, and less than half of these areas are specifically set aside to protect biodiversity rather than for recreation or other mixed use (Brooks et al. 2004). Further, Rodrigues et al. (2004) estimated that 12% of the nearly 12,000 animal species they studied live completely outside of any protected area, and Ferrier et al. (2004) estimated that 43% of *all* terrestrial plants and invertebrates live in these "gap areas." A number of studies have found that the persistence of the numerous organisms living within protected areas or native habitat fragments depends to a significant extent on habitat outside of such areas—that is, the matrix of the surrounding landscape (Daily et al. 2001; Ricketts 2001; Stouffer et al. 2006; Tscharntke et al. 2007; Perfecto and Vandermeer 2008; Vandermeer et al. 2008). Such matrix areas very often are used for agriculture, as may be expected from agriculture's ubiquity. The need to integrate management of the matrix/gap areas in general and for agriculture in particular in order to produce a coherent conservation approach is thus quite clear.[11]

Today's accelerating decreases in biodiversity cannot be laid solely at the feet of intensive agriculture; nonetheless, agriculture directly and indirectly accounts for a number of (arguably the most significant) threats to biodiversity (Bruinsma 2003; Tscharntke et al. 2005). At the most extreme, overintensification or mismanagement of an agricultural area can destroy the capability of its ecosystem to support diverse life forms, creating and expanding literal and biological deserts (Hillel 1991; Sivakumar 2007; UNCCD 2004). And as was discussed in the previous section, economic pressures from certain forms of intensification, as well as urbanization and diet change, can increase rates of deforestation and its typical concomitant loss of biodiversity (Angelsen and Kaimowitz 2001; Buttel 1990; Schroth et al. 2004; Sloan 2007).[12]

Keeping these factors in mind, we will primarily analyze agriculture's effects on biodiversity from the perspective of habitat degradation and destruction; and to a lesser extent, environmental toxification. Given habitat degradation and

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[11] Although agriculture is our focus, it is worth noting that a similar discussion is taking place around forestry/agroforestry and commercial forestry (see also Schroth et al. 2004; Brockerhoff et al. 2008). .

[12] Poverty, often seen as a significant factor in promoting deforestation and environmental degradation, may play much less of a role in these phenomena than was once thought, especially in comparison to the effects of non-poor landowners (Ravnborg 2003; Gray and Moseley 2005; Sloan 2007).

destruction's primary role in biodiversity loss, and given that agriculture occupies (and has impacts on) a large and growing amount of land, it is abundantly clear that management of human food systems will significantly affect the progression of the biodiversity crisis and thus impose some of the most significant challenges to addressing it.

## Alternative production

The current global availability of 2,800 calories per capita per day can be taken as an apparent success of conventional agriculture (FAO 2007; IAASTD 2009; but see Note 8). That is, today's intensive agriculture provides sufficient food for global food security in terms of raw calories. Furthermore, the likely negative correlation between intensive agriculture and biodiversity has been reviewed. Is, however, an alternative system possible that mitigates this inverse relationship? That is,

1) Can alternative production methods provide a comparable level of (global) food security?
2) Can alternative production methods sustain a higher level of biodiversity?

### Food security from alternative agriculture

Many doubt then that alternative agriculture can comparably meet the needs of the world's growing population (Emsley 2001; Fresco 2003; Avery 2007). These researchers and others have maintained that only intensive industrial agriculture is capable of producing the high yields necessary to feed the world, and that alternative agriculture is economically infeasible, requires higher management skill, and even that organic agriculture degrades the soil. Occasionally, alternative agriculture is so completely dismissed that it does not even bear direct mention (e.g., in Evenson and Gollin 2003).

However, there is a significant and growing literature specifically addressing the critiques above. Many scientists have obtained results contrary to the idea that alternative agriculture cannot provide enough food for the world. A review by Rosset (1999) and a recent international consensus report (IAASTD 2009) provide analyses suggesting that alternative methods used on small and family farms have great potential for productivity. These two works portray alternative routes to ample production by smaller, less chemically and mechanically intensive and more ecologically friendly farms. Additional published data shows that small farms almost always produce higher output levels per unit area than larger farms; this phenomenon has been called the "inverse relationship between farm size and output" (Assunção and Braido 2007; Barrett 1996; Cornia 1985; Feder 1985; and a review by Heltberg 1998).[13] Among the reasons cited for this relationship are: (1) multiple cropping; (2) more efficient use of irrigation; (3) relatively higher labor quality and supervision (likely due to the use of family labor with a greater stake in farm success rather than alienated outside workers), and (4) non-purchased inputs as opposed to the agrochemicals of large-scale intensive agriculture (Kirner and Kratochvil 2006; Lappé et al. 1998; Netting 1993; Oduol and Tsuji 2005; but see, Benjamin 1995; Bhalla and Roy 1988; Lamb 2003).[14]

Badgley et al.'s (2007) study found that alternative methods could produce enough food on a global basis to sustain the current human population, and potentially an even larger population, without increasing the agricultural land base. The study concluded that a hypothetical worldwide alternative agricultural system could produce between 95 and 157% of the calories produced presently, without land expansion and with no net increased resource use from the present predominately conventional system (see *State of the biosphere: global measures of food security* for a description of this study). This is in addition to the body of empirical and theoretical literature connecting alternative agriculture's utilization of higher crop diversity to higher yield stability—that is, less variation in yields from year-to-year (Di Falco and Perrings 2003).

The body of literature reviewed by Rosset (1999) and more recently by IAASTD suggests that in developing countries, the small family farm is central to long-term management and agricultural sustainability. Such systems may use methods based on thousands of years of experience (Ucko and Dimbleby 1969; Struever 1971; Altieri et al. 1987; Netting 1993). Prolonged tenure on the same

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[13] Citing Rosset, Vandermeer and Dietsch (2003) concluded that land reform (breaking up the inequitable concentrations of land possession present in most of the world) and redistributing the land among small producers would be the most sensible short-term solution. This, along with secure land tenure, has significant potential to aid food production, in addition to its roles in democratization and larger political reform (IAASTD 2009). Generally speaking, land reform is of a piece with food sovereignty and other broader food system issues that will need to be dealt with in order to achieve sustainability, food security, and conservation (see also Notes 15 and 25, and Conclusions).

[14] If this makes the popularity of conventional farms perplexing, bear in mind that a primary advantage of conventional techniques is that they are much less labor intensive: a single agriculturalist can work far more land using conventional methods. Conventional methods' use of synthetic inputs also externalizes a number of societal and environmental costs, meaning that society subsidizes lower *apparent* production costs through decreased health, biodiversity and environmental quality. Direct monetary subsidies can also dramatically favor large farms over small ones (USDA 2009).

land means that the small farmer risks collapse of her or his farm in the long-term due to ecological degradation when wagering short-term gain against sustainability. Awareness of this long-term risk and, importantly, secure land tenure, can lead to higher and more stable production from family farms in comparison to larger farms in the same region, in part due to practices to minimize and reduce degradation (D'Souza and Ikerd 1996; Rosset 1999; Templeton and Scherr 1999).[15] Labor-intensive practices may be used to enhance soil conservation and fertility, allowing harvesting with minimal reliance on industrial inputs (Netting 1993).

The FAO (Bruinsma 2003) found that the use of integrated plant nutrient systems (IPNS) can provide for 10–30% greater efficiency in fertilizer use, and therefore the ability to apply less fertilizer for the same benefit level. The FAO also found that no-till/conservation agriculture (NT/CA) avoided the problems of degradation seen in conventional soil tillage, reduced the need for herbicides and raised yields by 20–50% over conventional methods. Additionally, Bruinsma (2003) found that the introduction of plant protection based on integrated pest management (IPM) was able to help avoid overdependence on pesticides while generating good to dramatic improvements in production, and a simultaneous reduction of costs in some cases. Similar results for IPNS, NT/CA and IPM have been found by Pretty et al. (2003, surveying 89 projects), Pretty et al. (2006, surveying an additional 218 projects), and Uphoff (2007), among others. Insofar as such methods reduce the use of synthetic fertilizers and pesticides, they also reduce the impacts from the production and transport of these inputs (see *Production method and biodiversity* for further discussion of such impacts).

While such examples provide some evidence that alternatives to intensive agriculture exist that may be viable in terms of necessary yield and sustainability, the economic viability of alternative practices remains to be addressed. As Madden (1987) points out, an agricultural system requiring financial suicide on the part of the farmer cannot be said to be sustainable. However, there are indications that the economic performance of alternative farming systems can be comparable to, if not better than, that of conventional farming systems. This is supported by work at national levels as well as within-farm levels (Greene and Kremen 2002, 2003; Madden 1987; Offermann and Nieberg 1999; Pacini et al. 2003; Padel and Lampkin 1994; Smolik et al. 1995). The findings of Smolik et al. (1995) support the conclusions of Rosset (1999) by suggesting that the widespread adoption of organic farming in their study system would tend to counter the trend of increasing farm size: conventional farming was calculated to require a greater area for the same level of profitability as a smaller organic farm in most cases. Additionally, supporting the viability of alternative agriculture in terms of the level of difficulty in its management is the work of Pacini et al. (2003), Lockeretz (1995), and the comprehensive survey of sustainable farms by Pretty and Hine (2001). The conclusions from these studies imply that the management requirements of sustainable agriculture, if at all higher than in conventional agriculture, can be overcome with local and international educational initiatives — although the political, logistical, and economic obstacles to such initiatives may be significant in some cases (Pretty 2008).

On the other hand, Bruinsma (2003) points out that organic agriculture carries the financial burden of finding a different set of appropriate inputs (i.e., non-GM seeds, green manure), and that an increase in the supply of organic foods would lead to a decline in the premium prices assumed to maintain profitability. However, in addition to the work cited above, a number of studies point out the extremely high direct and indirect costs of conventional agriculture (including decreased energy efficiency and environmental damage from pesticide and fertilizer run-off and the burning of fossil fuels), and that organic or alternative agriculture can be comparably profitable, in some cases even when subsidies are not subtracted from the profitability of conventional farming (NRC 1989; Faeth and Crosson 1994; Stockdale et al. 2001; Tilman et al. 2002; IAASTD 2009). Profits from alternative agriculture may also be less variable, providing farmers with greater predictability and flexibility. Research showing significantly greater carbon sequestration, higher energy efficiency, and lower carbon emissions from alternative agriculture raises the possibility of future income streams from payments for ecosystem services or cap-and-trade arrangements (Di Falco and Perrings 2003; Pimentel et al. 2005; Borron 2006; Pimentel 2006; IAASTD 2009).

In sum, there is evidence to support the proposition that alternative agricultural methods can provide enough food, on the global scale, to provide a comparable level of food security as would conventional agriculture. Further, there is even a real possibility that alternative agriculture can provide food security more efficiently and with higher profits for small farmers.

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[15] A full analysis of the dynamics of farm size is not possible in the present work. However, it is important to note the "Goldschmidt Hypothesis": that community welfare will be significantly higher in regions where agriculture is organized around smaller-scale farms than in regions dominated by a small number of large farms (Goldschmidt 1978). In the 60 or so years since his original study, a number of restudies by sociologists have "offered at least tentative support for his conclusions" (Lyson et al. 2001); and few direct refutations.

## Production method and biodiversity

Thus far, the information reviewed implies that (conventional) agricultural intensification is unnecessary for global food security because alternative agriculture may have the potential to generate as much or more food. When one additionally considers agriculture's effects on biodiversity, and the effects biodiversity may have on system stability, sustainability, adaptability, and resistance to invasive organisms (Hooper et al. 2005), it becomes clear that further evaluation of the mechanisms of biodiversity's interactions in agriculture is necessary. This section will review such mechanisms and how they are typically affected by alternative and conventional practices, keeping in mind that agriculture is an important, but far from the only, aspect of human food systems affecting biodiversity and sustainability.

Broadly, a recent meta-analysis found that alternative agriculture increases biodiversity in most cases, with an average of 30% more species and 50% more individuals, although this varied among the types of organisms studied (i.e., different taxa—species, genera, families, etc.) and spatial scales (Bengtsson et al. 2005). For this reason and others, agricultural ecologists commonly find it useful to distinguish between *planned* and *associated* biodiversity in agroecosystems (Perfecto et al. 1997; Swift et al. 1996; Vandermeer et al. 1998). Planned biodiversity is determined by the combination of the biological components chosen by an agroecosystem's manager (i.e., crops/crop varieties and livestock) and those eliminated (i.e., weeds and herbivores). In addition to this biodiversity planned by the manager, there can be a great number of species and species varieties distributed throughout an agroecosystem as a result of interactions with the species and land management practices chosen by him or her. The amount of inputs, the degree of mechanization, and the size and type of crops or livestock determine the structural complexity and possible linkages available to other organisms, in effect determining the number of niches available[16] (Lavelle and Pashanasi 1989; Matson et al. 1997; Moguel and Toledo 1999; Armbrecht and Perfecto 2003). In turn, the planned and associated biodiversity along with the land management practices complexly influence various ecosystem functions, including resource capture by the crops, pest and disease resistance, carbon sequestration, stability in response to environmental perturbation, and reproduction (Vandermeer et al. 1998; Tscharntke et al. 2005, 2007; Kibblewhite et al. 2008; Shiva 2008). Specifically, a positive association between planned and associated biodiversity has been, according to Vandermeer et al. (2002), established "beyond credible doubt" for vertebrates, arthropods, and non-crop plants, based on their review of over 30 studies on biodiversity and ecosystem functioning. Associated microbiological biodiversity showed either a positive or insignificant association with planned biodiversity in the papers reviewed; with positive, negative, or insignificant associations shown as well elsewhere (i.e., see Hooper et al. 2000; Kibblewhite et al. 2008).

Recent works further support the findings of Vandermeer et al. (2002) especially, but not exclusively, for the biodiversity of macroscopic organisms. Perfecto and Vandermeer (2008) review much of this literature, especially the extensive work from coffee agroecosystems, which has provided broad evidence that higher associated biodiversity in a number of taxa (including microorganisms) corresponds with higher diversity and density of shade trees in such systems. Other examples from the literature include: evidence of increased associated biodiversity in birds, dung beetles, and other fauna as a result of planned structural diversity (i.e., vertically complex edge habitats) (Hughes et al. 2002; Perfecto and Vandermeer 2008); Luck and Daily (2003) suggest that increasing planned biodiversity in the Costa Rican countryside would support higher bird diversity that could, in turn, contribute substantially to the dispersal of rain forest plants and thereby encourage even further associated biodiversity; and Beecher et al. (2002) found that organic cornfields had higher bird diversity and were more important to conserving biodiversity than conventional systems. Similar results can be found in a number of studies from cacao, silvopastoral, and home garden agroecosystems (Perfecto and Vandermeer 2008). These studies reflect what we consider to be a representative sample of the pertinent literature, thus we conclude that it can reasonably be expected that macroscopic, and in some cases microscopic associated biodiversity will increase with planned biodiversity.

Further exploring differences in planned, and therefore, associated, biodiversity, it is useful to compare what pertinent, if broadly drawn, differences there might be between alternative and conventional agriculture. While there is not a direct line of practices and procedures to connect them on the spectrum between their extremes, a generalized outline can be made (Swift and Anderson 1995; Swift et al. 1996). What follows is, again, based on what we consider representative samples of a very large and complex literature.

Two general goals are part of modern agriculture: more frequent use of the same area of land (i.e., decrease or elimination of fallow periods) and increased specialization of productive species (loss of plant biodiversity, usually in the pursuit of higher yields and ease of mechanization). The extended fallow periods in traditional agriculture are abandoned in order to use the same area of land every year

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[16] The number of ecological niches is, roughly speaking, the number of resource and habitat "openings" that organisms may occupy and exploit.

for continuous production. Such loss of extended fallow periods perhaps has its most notable effect in agroforestry systems. In such systems, the change from extensive, shifting cultivation to shortened fallow periods or continuous cultivation and the use of chemical fertilizers, can threaten the ability of the system to conserve native forest and its associated biodiversity of wild plants, terrestrial and understory insectivorous forest birds, and organisms that live only or primarily in the secondary growth of long-term fallows (Jessup 1981; Whitmore 1984; de Jong 1997; Finegan and Nasi 2004; Somarriba et al. 2004).

Outside of agroforestry, modern agriculture's more frequent use of the same area of land for annual cropping results in frequent, short, or bare fallows which have been found to be disruptive to communities of micro- and meso-scale soil organisms, especially when compared to perennial crops (Campbell et al. 1991, 1999; Neher and Campbell 1994; Chander et al. 1997; Zentner et al. 2004).[17] The key factor in mitigating such disruptions and in maintaining soil health and biodiversity appears to be a steady feed of below-ground carbon substrate, as provided by continuous vegetative cover and root systems, whether this is provided by perennial crops, leguminous green manure, or non-leguminous cover crops. Synthetic (inorganic) fertilizers can also mitigate soil degradation and concomitant biodiversity loss to some extent in intensive conventional systems, independent of the fallow regime (Kibblewhite et al. 2008; Pimentel et al. 2005); however, inorganic fertilizer application (especially over-application) can itself degrade soil quality in some instances (Biederbeck et al. 1996; Ukrainetz et al. 1996; Demkina and Anan'eva 1998), although this is likely not a direct toxic effect, but rather the result of associated practices and complex, poorly-understood interactive effects on soil carbon cycles (Kibblewhite et al. 2008).

Other differences in normative practices between conventional and alternative agriculture also affect soil health and biota. Increases in mechanization (tillage and compaction from machinery) have nearly-universal negative effects on populations of soil communities, from microbes to Carabid beetles. The effects of pesticides broadly mirror those of mechanization—although in both cases species or functional group population sizes are sometimes affected much more than biodiversity itself,[18] which may raise chances of local extinctions but is not necessarily detrimental to ecosystem functioning in the short-term. Such negative effects on population sizes and diversity in turn *can* have negative effects on yield, fertility and carbon sequestration, though much more research is needed in *all* areas studying soil health, intensification, and agricultural practices (Foissner 1997; Neher 1999; Pimentel et al. 2005; Fox et al. 2007; Kibblewhite et al. 2008; Tscharntke et al. 2005; Shiva 2008).[19]

Returning aboveground, biodiversity in the agroecosystem can be decreased further when traditional, diverse, locally adapted crop varieties with resistance to native diseases and pests are abandoned and intercropping is halted in favor of high-yield monocultures. Such extreme specialization can be encouraged or even dictated by adoption and intensification of mechanization (Vandermeer 1989; Altieri 1990; Buttel 1990; Salick and Merrick 1990; Ramakrishnan 1992). For example, in contrast to the seven domesticated species and several thousand land races of potatoes that Zimmerer (1998) found in traditional Andean agriculture alone, Soule et al. (1990) found that between 10 and 20 different crops provide about 85% of the world's calories. The narrow range of crop species planted in modernized conventional systems additionally represents a loss of structural diversity as it replaces multi-strata vegetation and complex crop patterns (Vandermeer 1989; Fageria 1992; Vanderplank 1984, in Swift and Anderson 1995). This loss of crop diversity, along with lower or nonexistent levels of non-grain biological material and the increasing size of planted monocultures, increases isolation from fragments of native habitat and contributes to losses in planned and associated biodiversity, especially with respect to populations of invertebrate consumers, predators, and pests (Altieri and Liebman 1986; Tscharntke et al. 2005, 2007; Klein et al. 2006). The genetically uniform, high-yielding hybrid crop varieties of conventional agriculture are additionally often less resistant to pathogens and pests, especially given the highly dense and structurally simple concentration of food or host plants—meaning that they may fall prey to new or adapted parasites (Heller and Keoleian 2000; Margosian et al. 2009).[20] When

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[17] Although this may describe both conventional and alternative agriculture, alternative agriculture tends to more frequently emphasize rotations, increased fallows, and cover cropping rather than bare fallows.

[18] "Functional groups" are groups of organisms that perform similar or the same ecological roles, such as respiration or nitrogen fixation.

[19] Although a generalized narrative is attempted here, it is vital to note that there are considerably variable results in research on soil responses to cultivation. Hooper et al. (2000) provides some indications of the complexities and disagreements within the literature; Neher (1999) provides a more specific review of soil community reactions to agriculture; a more recent but less specific overview is provided in Kibblewhite et al. (2008).

[20] Such loss of diversity may also compound future problems. A number of domesticated biological resources and genetic material are very likely not sustainable independent of the conservation of a stock of wild resources. Protection of on-farm cultivar diversity and wild relatives ("in situ conservation"), as well as a recognition of the importance of ethnographic and cultural knowledge in the use and propagation of biodiversity, will be needed along with off-site (ex situ) preservation in order to respond to the local needs of marginal farmers and future social or environmental changes (Altieri et al. 1987; Weissinger 1990; Dahlberg 1993; Jarvis and Hodgkin 1999; Almekinders and Elings 2001).

conventional varieties are monocultured, the pests attracted by such a buffet tend to dominate the agroecosystem at further expense of biodiversity; while the planned and associated biodiversity of polycultural plots often includes useful pest predators, which reduce pest damage in many cases, thereby increasing yield (Root 1973; Andow 1991; Kromp 1999; Gurr et al. 2003; Loya-Ramirez et al. 2003).[21] Indeed, in contrast to the large reductions in biodiversity that are regularly seen in monocultural and conventional agroecosystems, a significant amount of research notes the benefits to biodiversity of indigenous planned polycultures (Altieri et al. 1987; Oldfield and Alcorn 1987; Toledo 1990; Leakey 1999; Moguel and Toledo 1999; Altieri 2000; Finegan and Nasi 2004; Somarriba et al. 2004), and even certain forms of swidden agriculture (de Jong 1997; Schmidt-Vogt 1998; Fox et al. 2000).[22] In turn, local-scale agricultural diversity is both supported by and contributes to biodiversity at the landscape level, as part of a more broadly diverse mosaic of agriculture and natural habitat fragments (Tscharntke et al. 2005). And lastly, more diverse agricultural systems offer the possibilities of redundancies and resilience, from the diverse responses of its resident organisms (i.e., while some important nitrogen fixers may decrease activity after an environmental change, others might increase activity and thus compensate); and the diversity of ecosystem functions such organisms may perform. This can be a form of insurance for temporal and spatial sustainability. This is especially important when considering changing yearly or long-term environmental variation (e.g., global climate change, disaster and extreme weather events like hurricanes, droughts or floods) and landscape- or regional-level conservation (Holt-Giménez 2002; Hooper et al. 2005; Tscharntke et al. 2005; Kibblewhite et al. 2008; Lin et al. 2008).

Without such insurance and resilience, systems that are intensified and simplified end up with their yield (and profit) dependent on an optimized environment, defined by high-input, irrigated, fertile zones free from disease, rather than the local conditions in any given area (Witcombe et al. 1996; Ceccarelli et al. Unpublished manuscript, in Rhoades and Nazarea 1999; Tilman et al. 2002). To maintain an optimized environment, wide-spectrum pesticide applications are used to control pests, but they can also wipe out useful pest predators that may come as stragglers or newcomers (Swift and Anderson 1995). Pests meanwhile persist through pesticide-resistant individuals and their progeny, leading to continually diminishing effect of pesticide applications (i.e., the "pesticide treadmill") (van den Bosch 1978; Pimentel et al. 1991; Russell 1993; Vandermeer 1996). Through accumulation up the food chain, over-application, and runoff, these pesticides can additionally flow into the ecosystem outside of the farm and, along with fertilizer runoff, damage environmental and human health and cause secondary reductions in biodiversity in the surrounding environment, e.g., eutrophication and the infamous "Dead Zones," (Pimentel et al. 1992; Steingraber 1997; Tilman et al. 2002; Devine and Furlong 2007; Tonitto et al. 2007; IAASTD 2009).[23] Further, as with inorganic nitrogen, the production and transportation of synthetic pesticides is an energy-intensive process leading to increased emissions of greenhouse gases, threatening biodiversity on a broad scale via global climate change (Pimentel et al. 2005; Ehrlich and Pringle 2008).

The diversity of alternative agricultural practices seems to represent a distinctly different tack than conventional agriculture. Although the current agricultural regime provides a sufficient global (caloric) supply of food, with approximately 98% of agricultural land under conventional management and 2% under alternative methods, there are often serious reductions in biodiversity as a result. Following from the previous results, global food security is theoretically possible even if the current regime adopts alternative agriculture in whole or in part. Given that and the review presented in this section, the decision to use alternative agriculture may allow us to feed the world while preserving a higher level of planned and associated biodiversity at local, regional, and global levels.

## State of the state: regional food security and biodiversity

The analysis thus far has taken a broad view of both food security and biodiversity. Having presented evidence that sufficient food (on a hypothetical, average caloric basis) is being produced for the global human population, and that sufficient food could theoretically be produced as well

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[21] In a small number of cases, monocultural plots have maintained comparable levels of associated biodiversity in certain arthropod taxa (Butts et al. 2003; Melnychuk et al. 2003).

[22] Organic monocultures, of course, present many of the same problems as conventional plots. The notable exceptions to this are a) lower run-off of agricultural nutrients (see Note 23), b) avoidance of synthetic pesticides' detrimental effects on health and biodiversity, and c) lower fossil energy use and costs. The latter of these benefits may also disappear if organic nutrients (i.e., from animal manure or "green manure" crops) are not sourced on-site or locally (Pimentel et al. 2005), resulting in the contradictions of so-called "industrial organic" agriculture (Pollan 2006).

[23] It is of course not necessarily true that the non-synthetic fertilizers and pesticides used in alternative agriculture are always applied appropriately and always experience lower run-off. However, recent studies have observed comparable or significantly lower levels of nutrient leaching in some alternative systems (Kramer et al. 2006; Tonitto et al. 2006).

under an alternative production regime supporting biodiversity, questions of regional food security arise. Global food security is a necessary result of regional food security, without the reverse being true: the fact that some regions of the world have sufficient food does not mean that all regions have food security. Global and regional biodiversity have a somewhat more complex relationship. There is not necessarily a given amount of biodiversity each region "should" have (as opposed to relatively absolute caloric and nutritional intake requirements for human well-being), with still-contentious debates taking place over the correlations, or lack thereof, of higher or lower levels of biodiversity to desirable ecosystem properties like stability, resilience, recovery, and production/yield (Hairston et al. 1968; MacArthur 1955; May 1972; DeAngelis 1975; Pimm 1979; Frank and Mcnaughton 1991; Hooper et al. 2005).[24] The consequence of this lack of absolute standards is that global biodiversity can be constructed as biodiversity maintained under an average or weighted extinction rate, leading to an approach to conservation that proposes that human impacts on biodiversity loss should be minimized to the extent possible, the limit being the background extinction rate of any given ecosystem or region. Different ecosystems have different background extinction rates, so that even in an "optimally biodiverse" world, some regions could have higher "acceptable" rates of extinction than others. This is a completely different conclusion than is acceptable for food security, where the goal is for each person in every place to have access to somewhere in the range of 2,200–2,800 calories per day (although, like biodiversity conservation, the means to achieve this necessarily involves issues throughout multiple hierarchies of scale). New local habitat can even, in principle, be created as old habitat is destroyed, or matrix quality retained such that endemic biodiversity reduction or species loss in general is minimized at the farm or even landscape level (Hanski and Gilpin 1997; Hanski 1999; Vandermeer and Carvajal 2001; Perfecto and Vandermeer 2002, 2008). Thus the idea of "making up" (e.g., compensating for) gaps in regional biodiversity so that it all averages out is a contrast to the goals of food security, which at minimum would need to meet the standards of egalitarianism of universal and equal access to sufficient and satisfying food (though not necessarily access to all of the same foods).

Therefore biodiversity analyses are by definition simultaneously local, regional, and global in scope, with each level requiring differing but complementary approaches, units of analysis, and data. Local information is high in detail but has limited scope; global analyses provide understanding of cumulative relationships and broad scope, but little resolution. While the actual act of agricultural production necessarily has its most immediate effects on local and landscape biodiversity, the effects of food systems span the local to global—meaning sustainable local agricultural changes are necessary, but insufficient, for global sustainability. Extended discussion of the larger-scale effects of food production on the environment and economy (e.g., global climate change for one) are ignored here by necessity; the reader is referred to, among others, Lockeretz (1989), Steingraber (1997), Tilman et al. (2002) and Pollock et al. (2008, special issue on sustainable agriculture). Given the evidence that global food security is possible in a manner less antagonistic to biodiverse ecosystems than current agricultural practices, and therefore local and global biodiversity conservation, the question before us reduces to the following: Is it possible to guarantee local food security with alternative agricultural methods?

This is not by any means a simple question with an easy resolution. Having established the productive capability of alternative methods, the difficulty involved in local food security is in part a question of distribution in the increasingly global nature of today's economic and social world. Alternative agriculture was traditionally considered by its very nature to be different from the cash crop and export agriculture that characterizes much of food production today—although this is changing (Pollan 2006; see also Note 22). Even when it is possible to produce food using alternative agricultural practices in a fashion similarly oriented towards globalization and current export/import regimes, it is considered undesirable for a number of reasons by many practitioners, researchers, and advocates of alternative methods. Present global food surpluses have typically led to lowered global food prices, decreasing many small farmers' economic power and in turn decreasing their actual food security, as measured by the ability to obtain food (Drèze and Sen 1989; Lappé et al. 1998; Heller and Keoleian 2000; Rocha 2001). Pinstrup-Andersen (2003) notes that distribution of global food

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[24] In an extensive consensus review by Hooper et al. (2005), it was concluded as "certain" that system responses to biodiversity and biodiversity loss could be idiosyncratic (depending on ecosystem and its particular species and functional groups, for example); that some systems are initially insensitive to diversity, but that "more species are needed to insure a stable supply of ecosystem goods and services" over larger areas and time periods. They had "high confidence" that certain species combinations were complementary (meaning that they could increase productivity and nutrient retention as compared to a less diverse system); and that under similar conditions, susceptibility to invasion by exotic species was generally lower with higher diversity, and that having a range of species with different responses to disturbance can help increase stability, meaning that maintaining a diversity of species with diverse characteristics helps maintain a range of management options. However, determining the relationships between biodiversity and different ecosystem properties was found to require significantly more research, greater experimental work, and incorporation with the effects of various other drivers of global change.

surpluses lacks feasibility due to infrastructure constraints and would ultimately hurt the 75% of the world's poor and food insecure populations living in rural areas by co-opting the food markets they depend on for income.

Further, it is often maintained today that food insecurity stems from a lack of "food sovereignty", defined as the ability of a region or people to define their own agricultural, food, and land policies that are appropriate ecologically, socially, economically, and culturally (International Steering Committee of the Forum for Food Sovereignty (ISC-FFS) 2003). The lack of such can be seen as a failure of economic markets (Rocha 2003, 2007), independent of the biological situation. A full analysis of forces combating or aiding food sovereignty and their motivations is beyond the scope of this paper; the reader is additionally referred to work by Patel (2008), Daly (1996), Sen (1984), and relevant publications by the nonprofit organization FoodFirst. A cursory examination can also be found in the Conclusions of the present work.

## Regional and local food security and biodiversity conservation: tentative successes

The obvious alternative to complete global redistribution of food is to enhance self-sufficiency on a regional and subregional basis. In today's globalized and still trade-focused world, greater food self-reliance runs contrary to many trends. Despite the goals of the 1996 World Food summit, reaffirmed in 2003, Pinstrup-Andersen (2003) asserts that it is a myth that the eradication of food insecurity is truly treated as a high priority by national governments, especially in light of the dubious progress made since 1996. A very few countries, including Cuba (Funes et al. 2002; Pretty 2002; FAO 2006; Wright 2005) and Brazil (Hall 2006; Rocha 2009) appear to have taken sustainable regional food security as a serious goal. Many more countries in theory could provide food security at the national level but do not have local food security, much less food sovereignty, as a goal. Additionally, the direction of agricultural policy in the developing world is still somewhat uncertain, six years after the breakdown of the World Trade Organization meeting in Cancun in 2003 (Nederveen Pieterse 2004; Ryan et al. 2008; Obama 2009). It is therefore instructive to examine case studies to see what has been achieved today in terms of regional food security and greater food self-reliance.[25] Of the two cases presented, Cuba has experienced widespread adoption of alternative methods, while adoption in the Brazilian case has been variable—although as we have seen, in terms of productivity, alternative and conventional methods are apparently comparable.[26]

The program in Cuba appears to be by far the most ambitious. Cuba's food security program includes significant land reform, in the form of breaking large conventional state farms into smaller, cooperatively owned organic operations, starting new organic farms, and fostering urban and peri-urban agriculture (pers. obs.; Funes et al. 2002; Wright 2005). Increases in internal production of roots, tubers, vegetables, and beans have been reported (though there have been decreases in other food categories), and reports indicate that produce for the capital city of Havana is almost entirely supplied by alternative agriculture in, or on the periphery of, the city itself (see Note 4 for more on urban agriculture). These gains have been made despite the exigencies created by the collapse of the socialist bloc and the "Special Period" beginning in 1991 (Wright 2005). Though Cuba is still heavily reliant on imported agricultural inputs and food, available data indicate that acute food shortages have been largely eradicated due to improved national production (Funes et al. 2002, 2009; Koont 2004). Cuba has seemingly also already met the Millennium Development and World Food Summit Goals for 2015 (Wright 2005), with less than 2% of its population regarded as undernourished and an estimated availability of 3,200 calories/person/day (FAO 2006). In terms of biodiversity and agriculture in Cuba, some farms have up to 180 species under cultivation, and integrated polycultures appear to be becoming the norm (pers. obs.; Funes et al. 2009).

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[25] Since the original writing of this paper, local food has gained increasing attention and popularity, especially in the US and Europe. This can be seen in a number of recent popular books, such as *The 100 Mile Diet* (Smith and MacKinnon 2007) and *The Omnivore's Dilemma* (Pollan 2006), and in the popular press. Groups such as Slow Food and various urban gardening movements seem to be on the upswing, as is the growth of farmers' markets (USDA 2006). And of course, questions related to local food systems continue to be examined in the academic literature (see Pretty et al. 2005). It is not, however, solely scale or localness that are important, but also the democratization and effective decentralization of responsibility and power within local geographies—issues of social justice and equity that once again link to the production and distribution of food at scales involving, but extending beyond, the local (Prugh et al. 2000; Batterbury and Fernando 2006; Breitbach 2007). These issues cannot be fully addressed here, but they do reinforce previous points regarding regional food security and food sovereignty. Additionally, the case studies to be presented from Brazil and Cuba remain considered food initiatives par excellence by many, and can be considered of a piece with larger trends towards land reform and local and just food systems.

[26] Brazil, as with other developing countries, will face significant challenges to food security, conservation and the overall economy with global climate change and the rise of biofuels (see Sawyer 2008). Cuba will also doubtlessly be affected, but anticipating the nature of the effects is made difficult by its rather unique sociopolitical situation and political economy.

Belo Horizonte, in the state of Minas Gerais in Brazil, is home to 2.5 million people, and one of the most comprehensive and ambitious regional food security programs in the world. In 1993, the city committed itself to the concept of food security as a right of citizenship with the creation of a new Secretariat of Municipal (Food) Supply (*Secretaria Municipal de Abastecimento*, or SMAB). Nutrition, equitable and efficient food distribution, and local supply are among the major goals of the Secretariat's programs (Aranha 2000). SMAB has seen reductions in infant mortality and infant malnutrition of at least 50% since its inception, and boasts significant citizen participation in its programs, such as the 12,000 people per day served at the city's subsidized "Popular Restaurants" (pers. obs.; Rocha 2001; Alves et al. 2008). SMAB's progress on malnutrition and infant mortality has already surpassed the Millennium Development and World Food Summit goals, while Brazil as a whole is still progressing towards them (FAO 2006; Prefeitura Municipal de Belo Horizonte (PMBH) 2006; Rocha 2009). Although the aims of the program include guaranteeing its citizens adequate access to and an improved distribution of food, in part by encouraging local supply, alternative agriculture is not itself the fundamental focus of the program. It is, however, encouraged through a program supporting organic farmers' markets and is also informally encouraged, since many producers use alternative methods out of tradition, personal preference, or in search of price premiums. SMAB is developing an office for educational information on alternative methods (Rocha 2003; Z. B. Souza, pers. comm.). Further, farmer participation in SMAB's programs has been tentatively linked to increased ant biodiversity in the landscape around the city via changes in farmer practices (Chappell 2009). Given the evidence reviewed in the present work, it should be equally possible to support the city's gains in food security using alternative agricultural methods and therefore expand on the modest increases in biodiversity we have seen.

Though its administrators view their work as having just begun and hesitate to call SMAB a success already, its programs nonetheless serve as tentative examples of the possibilities of increasing regional food security. Indeed, Belo Horizonte has won several international awards, most recently the World Future Council's Future Policy Award. The Brazilian national food security program, *Fome Zero*, has also been influenced by successes in Belo Horizonte (and in São Paulo state; Bentley 2006; Chappell 2009), although the level of success of the national program remains to be seen, due to a dearth of regular large-scale outcome monitoring (Defourny 2006). Federal administrators have outlined a number of successes and their plans to expand on them, using a comprehensive and multi-sector approach as is used in Belo Horizonte (Rocha 2009).

## Conclusions

The evidence to date strongly suggests that both biodiversity conservation and food security can be effectively addressed using alternative agricultural practices. Although the majority of food insecurity at present is caused not by a lack of available food or insufficient agricultural production but by poverty and problems of socioeconomic access, alternative agriculture nonetheless does appear capable of producing sufficient yields. The evidence also supports the intuitive conclusion that alternative agriculture, which is generally targeted at sustainability and compatibility with biodiversity conservation, is indeed on average better for biodiversity conservation than conventional agriculture, which usually (though not always) targets increases in yield to the exclusion and even detriment of direct concerns about biodiversity, equitability, and food access (IAASTD 2009). Considering the significant environmental and health effects of conventional agriculture and its relative resource inefficiency compared with alternative practices, one could go so far as to say that in the face of diminishing land and fuel resources and likely future price increases, it is conventional agriculture which is a luxury we can no longer afford.

Based on this, we feel it is time to get beyond debates of alternative production versus conventional. Today's problems with hunger and obesity seem to have less to do with production method than a productionist/consumerist culture; that is, yield increases do not appear to be a solution to the existence of hunger (and micronutrient deficiencies), and yield increases in staple crops like corn and wheat certainly seem unlikely to solve problems of overconsumption like obesity. In a world where obesity and hunger co-occur, it seems beside the point to argue about yield increases, and with evidence that sufficient food can be produced using alternative methods, it is time to move past reservations about investing in and converting to alternative agriculture (barring, of course, substantial refuting evidence in the future) and on to doing it.

Although the human population is still growing, the most recent increase in food insecurity and the ballooning of the numbers of malnourished from 850 million to approximately a billion, an increase of about 17%, is not the result of the population increasing by 17% over the past several years, nor of yields going down 17%. Increases in food prices have been the strongest factor, and these increases in turn reflect in part the rise of biofuels and increases in petroleum prices (FAO 2008). The intensive energy requirements of conventional agriculture thus represent another hidden cost of these methods beyond losses of biodiversity and ecosystem services and environmental toxification: the higher energy requirements mean greater dependence on fossil fuels, meaning in this case that conventional agriculture was especially susceptible to direct shocks in fuel prices, with tragic results. One potential lesson from this is that, if we as a people agree about the existence of widespread hunger, that addressing it is a moral-ethical imperative, and that conserving biodiversity fulfills functional as well as (for a subset of people) moral-ethical imperatives, then we must be open not just to new (alternative) methods of production, but to new approaches to food choice and diet.

## Driving nature in the future

Agriculture in general represents a form of human triumph in driving nature to provide increased amounts of valuable functions. Much useful research remains to be done on how to continue to improve and optimize these functions (and not just yield). However, in terms of food security, the challenge now perhaps has tipped towards how to drive human nature towards a more sustainable system. We say this somewhat tongue-in-cheek; neither economic principles of self-interest nor empirical research on human behavior show that humans are "naturally" programmed such that cooperation and sustainability cannot be accomplished or require driving a major overhaul of human nature (not that the tasks before us are by any means easy; they just do not require the wholesale alteration of supposedly inalterable traits) (Ostrom 1990; James and Rassekh 2000; Prugh et al. 2000; James 2006). Rather, once we agree to the propositions of the existence of hunger, the imperative to address it, and the imperative to preserve biodiversity, and given that alternative agricultural methods can provide the minimum requirements of sufficient food and improved biodiversity conservation, we must move to the next step. We must explicitly address remaining differences over implementation, priorities and ethics and examine and alter relevant institutional arrangements that generate, incentivize or maintain food insecurity and biodiversity loss.

We agree with Dahlberg (1993) that what must follow are extensive evaluations of the significant structural changes and democratization required in local, regional, national, and international institutions—evaluations that are insufficiently common and vitally important. To that end, we briefly examine some of the necessary steps and important questions that we see ahead.

We alluded a number of times to the fact that sufficient production in no way guarantees actual food security by itself (see Note 8). From this standpoint, we think the best framework to use in a more complete analysis of food security is that of Rocha's "Five A's" (Rocha 2003, 2007)[27]:

- Availability refers to the sufficiency of a food supply to meet people's needs;
- Accessibility refers to people's economic and physical ability to acquire food;
- Acceptability addresses the cultural and nutritional suitability of the available food;
- Appropriateness evaluates the ecological sustainability and the safety of a food supply;
- Agency is the "right to knowledge, and knowledge of rights" – access to accurate information on food supply, quality, and safety in order to make informed market choices, rights to such information and to the other aspects of food security, and a competent sociopolitical system to guarantee these rights.

From these Five A's spring many of the important challenges ahead. It seems to us that a disproportionate research effort is put into Availability when the other four are relatively poorly covered. Indeed, too many discussions of food security seem to begin and end with Availability, with perhaps some lip service to Accessibility and to ecological Appropriateness, but no mention of Acceptability or Agency. This last seems to us a key area for contributions from political economy; the structuring of institutions from the international to the local level will determine much of the characteristics of Agency, and consideration of the right to food (at inter- or intra-national levels), food sovereignty, cheap food policies, trade and alleviation of poverty are what we see as top priorities for research (and action). Accessibility also fits into the context of political economy because poverty is one of, if not *the* major cause of food inaccessibility. In cooperation with policymakers and planners, measures to increase Accessibility, like public transportation, alleviating food deserts (an area with fast or junk food outlets but little or no access to healthy and fresh food, see Mari Gallagher Research and Consulting Group 2007) encouraging re-ruralization (Orr 1994), and urban agriculture will be key areas of focus.

We already have spent time here talking indirectly about Appropriateness, in terms of agriculture's effects on biodiversity, especially the significant role small farms would play. However, agriculturalists and ecologists will need to work together to continue to investigate agroecological interactions and landscape integration and to look beyond short-term biodiversity conservation to the more general concern of sustainability (which we will not discuss here). Alternative methods and agroecological research to specifically support small-scale rather than industrialized

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[27] Although Rocha (2007) does not explicitly mention or define "agency," she considers "the whole article to be in fact a justification of the importance of agency," and that "we cannot achieve the first Four A's of food security without *agency*." (*pers. comm.*). For an example of an in-depth case study analysis using Rocha's framework, see Chappell (2009).

agriculture will need to be reinvigorated, and with cooperation between ecologists and political economists, research to support these efforts will be needed, such as accurate valuation and incorporation of life-cycle costs and benefits of different food systems and diets, and the costs of non-food uses of agricultural products. A decentralized/small-scale/locally-focused food system could also be considered safer in terms of contaminants, disease, and even direct attack (Dahlberg 2003), an idea not yet much explored in the literature.

These suggestions are hardly exhaustive; they do not fully take advantage of the analytical framework of Rocha's Five A's or elaborate on the excellent work that has already been done in these areas. They leave out some issues that are not only multi-disciplinary, but which will require society-wide action, like adaptation to climate change (generally, and within agriculture); continuing environmental toxification; water and fossil fuel scarcity; outreach and mainstreaming of basic ecological literacy and understanding of food systems; debates on the appropriateness of economic values for nature[28]; and the variety of societal changes that will need to accompany technocratic advancements in food and ecology. Thus we humbly submit this as just one possible set of priorities, hardly exhaustive and very indebted to previous works and suggestions for research and action. We look forward to participating in the vital and urgent debates around how to implement and expand sustainable, alternative agriculture and provide food security. We hope, however, that we are collectively closer to the end of the debate on the production and sustainability benefits of "alternative versus conventional" than we are to the beginning; and that the dominance of the first "A", Availability, will yield to increased focus on the other four vitally important factors. Implementing this, or any of the other pertinent and valuable lists of suggested action and research (e.g., Ehrlich and Pringle 2008) will by no means be easy, but there are reasons to be optimistic about the possibilities—from the countless urban gardens, community food projects and burgeoning home gardens in the US and throughout the globe, to the innovative cases in Brazil and Cuba.

We look forward to the hard work ahead.

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[28] While "putting a price on nature" is anathema to many concerned with biodiversity, a blanket refusal to place economic value on such things risks sending the signal to markets that it has zero value. Rather like the value of a "statistical life" used in the calculation of how parties at fault should economically compensate people for deaths of their loved ones, it may sometimes be a necessary evil. However, the danger of sending the signal that nature has zero value must be weighed against the compaction and loss of information and constrained understanding of value embodied in a market approach. Only vigorous public discussion combined with further research will allow us to determine when such an economic approach is effective, wise, or ethical.

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