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Global change and the intensification of agriculture in the tropics

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zAbstract

Bridging understanding of local environmental change with regional and global patterns of land-use and land-cover change (LUCC) remains a key goal and challenge for our understanding of global environmental change. This meta-analysis attempts to bridge local and regional scales of LUCC by demonstrating the ways in which previously published case studies can be compared and used for a broader regional synthesis in the tropics. In addition to providing results from a meta-analysis, this paper suggests ways to make future case studies more widely comparable.

Keywords: Agricultural intensification; Tropical agriculture; Meta-analysis of case studies

1. Introduction

Human modification of the surface of the Earth is so substantial that some claim that the *entire* terrestrial surface of the Earth is altered by human action (Meyer and Turner, 1994; Redman, 1999). Indeed, our impact is so profound that we may have entered what Crutzen and Stoermer (2001) term "the anthropocene". While uncertainty surrounds the exact ramifications of these changes, the central role of human activity in altering the planet's biophysical and biogeochemical processes is unquestioned by all but the staunchest skeptics. Alongside the combustion of fossil fuels and other industrial processes involving the release of gases to the atmosphere, the alteration of land cover—the outermost covering of the terrestrial surface, including vegetated as well as barren and frozen surfaces—ranks among the most important human impacts on the planet (Raven, 2002; Steffen et al., 2004; Turner et al., 1990).

A multi-year, multi-investigator effort, the international Land-Use and Land-Cover Change (LUCC) Project studies the alteration of the surface of the Earth. This paper furthers the research agenda LUCC[1] by describing the comparative analysis of 91 case studies of agricultural change in Latin America, Sub-Saharan Africa, and South and Southeast Asia. At the outset of research we hoped that by analyzing a wide range of peer-reviewed case studies from the tropics we would find trends that described the pathways to intensification in agriculture. Such an analysis promises to be important to advancing agricultural change theory, and to contribute to the construction of more realistic models of global land dynamics. The article begins with a description of the methods employed, and proceeds to describe the range of outcomes analyzed, and the causal and mediating conditions associated with those outcomes. It concludes with a discussion of the implications for land change science (Rindfuss et al., 2004), and suggests recommendations for the conduct of future case studies of agricultural change. This study constitutes a

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[1]This study follows the LUCC Implementation Strategy (Lambin et al., 1999), which calls for the comparative analysis of case studies relating land use to land-cover dynamics in a given area. LUCC is a program element of the International Human Dimensions Program on Global Environmental Change and the International Geosphere–Biosphere Programme (see http://www.geo.ucl.ac.be/LUCC/lucc.html).

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companion to Geist and Lambin's studies of tropical deforestation (2001, 2002) and desertification (2004).

Understanding the ways that land-cover changes through altered land use—the manner in which the biophysical attributes of the land are manipulated—has long been a question in geography, agricultural economics, archaeology, and related disciplines (Butzer, 1982; Redman, 1999; Turner, 2002). LUCC studies are increasingly important as global change science recognizes that human and biogeochemical cycles are closely linked (Intergovernmental Panel on Climate Change (IPCC), 2001). Agricultural change is a crucial part of the Earth system by virtue of the sheer magnitude of agricultural land use. Ramankutty and Foley (1999; Ramankutty et al., 2002) estimated that almost 20% of the potentially vegetated surface of the Earth (about 18 million km^2) was under agricultural use as of 1992. While a doubling of agricultural production was accomplished during the past 35 years, another will likely be required over the next four or five decades to meet increasing human demands for food and fiber before population growth levels off with current agro-technologies (Alexandratos, 1995; Tilman, 1999).

Rather than more land under cultivation, the increase in food production will come from intensified agriculture. Agricultural intensification is a biologically important process because it involves the alteration of plants and animals from dependence on states and flows not managed by people to those managed by people. That is, increased inputs per unit area or time supplant natural processes of nutrient and biological regeneration. Conservation of biological diversity, hybridization of local seed varieties, and non-economic species eradication may all occur in the process of intensification (Mittermeier et al., 1998).

The hydrosphere is significantly affected by agricultural intensification. The diversion of streams and impoundment of surface flow alter hydrological systems to the degree that they can influence stream channel morphology, downstream vegetation and water supply, and evapotranspiration (Graf, 2001; L'vovich and White, 1990). Soil conditions also experience alteration under intensifying agricultural systems. Erosion, nutrient depletion, and carbon loss may be engendered by intensification (Altieri, 1995). Finally, agricultural intensification is often characterized by the application of agrochemicals and powered by petroleum-driven machines, with implications for the cycles of key biogeochemical elements, including the carbon, nitrogen, and phosphorous cycles. In addition to the surface aspects of land alteration, increasing evidence links Earth surface change with climate change (Watson et al., 2001). Focusing on land-cover dynamics, different processes (deforestation, desertification, urbanization, agricultural intensification) have very different implications for the structure and functioning of local ecosystems and operate quite differently depending on local social, economic, and political contexts.

Earth observation technology provides information on land-cover dynamics with increasing precision, accuracy, and frequency, but the ability to discriminate between types of land cover over broad areas is still quite rudimentary and subject to a suite of error sources (Duckham et al., 2003). Understanding the nature of these dynamics—describing the underlying land-use practices, and explaining the factors that give rise to them—poses a crucial, challenge to the advancement of global change science. Only by understanding the factors that shape land use can reasonable policies be set to influence future changes.

It is very tempting to associate the increasing human impact on the Earth over the past several centuries with the dramatic increase in human population to arrive at a simple causal mechanism, wherein population equals impact. This simple relationship (i.e., population = environmental impact) is modified to incorporate both the affluence (A) of the population (P) in question and the technology (T) with which people affect those impacts (I). The so-called IPAT or ImPACT identity (Ehrlich et al., 1993; Kates et al., 2001; Waggoner and Ausubel, 2002) offers an elegant and seemingly comprehensive identification of "driving forces" that apply at broad scales, but both sides of the equation become increasingly unsatisfactory as the scale of analysis narrows. At the regional and local levels, studies repeatedly demonstrate that a suite of variables—institutional, economic, biophysical, and cultural—are as important as the universal concepts embodied in IPAT. Recent attempts at operationalizing the variables in question do not lessen the difficulty of answering the fundamental human question: "What is, and what ought to be our relationship to the natural world?" (Kates, 1987, p. 532).

Ideally, these foundational human–environment questions could be addressed through "natural" experiments. These experiments would study a number of places in a standardized fashion, holding certain factors constant and observing the effect of variations in other key factors. Indeed, some of the most valuable studies of land-cover change processes have taken this approach (Kasperson et al., 1995; National Research Council (NRC), 1999; Turner et al., 1990). But this approach is costly and slow moving and, therefore, generally involves a small number of places. In addition, the important academic questions of the period in which the studies were commissioned feature prominently while neglecting sufficient assessment of other potentially important variables. In the commissioned studies noted, e.g., the importance of gender dynamics or ethnicity was not addressed—deemed important in later studies (Rocheleau et al., 1996)—while demography and market variables received excellent treatment. Gender dynamics are highlighted to demonstrate that different academic generations value at times distinct explanatory variables.

Other explanatory frameworks employ rich theoretical backgrounds such as common property, market, or policy factors that seem to highlight the causes of change at particular scales and at points in space and history. When scales of analysis change, however, these explanations prove inadequate, leading some scholars to revert to idiographic conclusions about their particular study. That is, the nuanced manner in which change occurs may lead to multiple studies that embrace radically different explanations of agricultural change, vexing attempts to develop broad conclusions. In this study, we hoped that comparing cases across theoretical and geographic ranges would reduce the nearly infinite causes of change to a handful of factors and that we could reduce, and identify necessary and sufficient conditions for change. As we demonstrate in this paper, the major variables supplied to the global change community as factors of change do play an important role in what researchers deem as important.

Given the difficulty of commissioning studies, other approaches to developing regional analyses are being undertaken. An approach implemented by various participants in global change research involves the examination of the corpus of case studies published by anthropologists, economists, geographers, political scientists, and other social scientists interested in land-use practices (Geist and Lambin, 2001; McConnell and Keys, 2005; Rudel, 2005; Angelsen and Kaimowitz, 1999; Rudel and Roper, 1996; Moran, 1995). This coordinated effort at the comparative, meta-analysis of case studies yields new insights and improved understanding of land-use and land-cover dynamics in the tropics, where important change occurs. Recent meta-analyses of tropical deforestation, e.g., elucidated a range of variables that operate along with, and sometimes in place of, population growth, to shape the patterns and rates of this key land-cover change (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2001; Rudel and Roper, 1996). Both Rudel and Roper (1996) and Geist and Lambin (2001) noted that the causes of deforestation proved complex as the factors varied by case study.

2. Methods

2.1. Framing the outcomes

Agricultural intensification is a complex process that includes the slowing or halting of agricultural expansion, increasing inputs to production, and increasing output per input (Boserup, 1965; Brookfield, 1964; Turner and Brush, 1987). While some agricultural intensification studies focus on increasing inputs, others fix their attention on outputs, with input and output changes not necessarily overlapping (Turner and Brush, 1987; Turner and Doolittle, 1978; Turner et al., 1977). For example, increasing inputs to a crop (e.g., labor) can maintain or slow the decline of per capita output. Conversely, a rise in productivity can occur by reducing some inputs (e.g., labor) in favor of others (e.g., mechanical or chemical technology). One useful framework for studying agricultural change differentiates between innovative intensification and non-innovative intensification (Laney, 2002). Innovative intensification describes the shift to a new techno-managerial strategy, resulting in higher output per unit of input, whether labor, land, and/or capital (Laney, 2002). Non-innovative intensification encompasses increasing inputs without a concurrent techno-managerial shift, which in the extreme leads to a leveling or possibly a decrease in output per unit of input, known as stagnation or involution, respectively (Geertz, 1963). Non-innovative intensification often involves an increase in the crop cover over the course of a given year through a reduction in the length of fallow, while innovative intensification may involve this and/or a shift to a new cultivar, the application of chemical fertilizers and pesticides, the use of petroleum-fueled machinery, and/or significant alteration in local hydrology. Any of these forms of intensification are relevant to global change.

2.2. Framing the conditions

Studies on the conditions under which intensification occurs investigate the relative importance of endogenous factors (e.g., natural population growth) under the control of local actors versus exogenous factors (e.g., government policy), especially by focusing on the ways these interact in complex, systemic ways (Robbins, 2001; Turner and Brush, 1987). What the case study literature makes clear is that these endogenous–exogenous relationships are variable; at times these variables represent necessary or sufficient conditions for change. Regardless of the theoretical underpinning, population growth and density frequently enjoy the limelight in land-cover change analyses. Indeed, two framing concepts are used typically to analyze how and why agricultural change occurs. Published in 1798, Malthus's *An Essay on the Principle of Population* claimed that population growth in England would soon outstrip food supply because population grew exponentially and food supply increased arithmetically. This idea is applied to other situations and underlies contemporary environmental concerns. The adherents to Malthus's thesis, dubbed neo-Malthusians or Cassandras, point out that the changes we bring to the planet and to food production systems in particular approach tipping points that promise to slide us into starvation and conflict (Ehrlich and Ehrlich, 1990; Ehrlich and Holdren, 1988; Kates, 1995).

In 1965, Boserup published *The Conditions of Agricultural Growth*, taking a contrary view to Malthus. Boserup (1965, 1981) contended that population growth increased agricultural production as innovation and technological shifts occurred and allowed for growing numbers. Lee (1986) and Turner and Ali (1996) suggest that Malthus and Boserup may in fact complement each other. ''They share various assumptions about the relationships among population, technology, and resource use but differ…in their views of the origin of technology. Malthus implies that technology is exogenous in…that its development is not necessarily linked into the population-resource condition. Boserup…grounds this development directly into that condition; technological change is endogenous to it'' (Turner and Ali, 1996, p. 14990).

Because population growth is common in regions experiencing agricultural change—especially the shift from mainly subsistence- to market-oriented production—it adds little explanation to why changes occur. In fact, the general existence of population growth and movement in these regions can confound interpretation, as it frequently is the only shared trait across separate regions. Thus, explanations arise that point to population as the primary cause of agricultural intensification and gloss over other candidate causes—affluence and technology at the regional level, and culture, market, or inter-ethnic relationships at the local level.

The roles of economic and institutional factors in shaping agricultural change are ambiguous and nuanced (Lambin et al., 2001). 'Institutions' in this analysis mean the ways that people organize their activities, including both formal rules and rules-in-use that govern people's differential access to and enjoyment of the benefits of natural resources for agro-silvo-pastoral and other productive and aesthetic purposes (Dietz et al., 2003; Ostrom, 1990). Specific examples of institutions treated in this study include property regimes and various governmental and non-governmental programs affecting people's access to capital, information, and technology. In this framework, institutions either facilitate or hinder land-use change, as do shifts in culturally related aspirations and desires.

Like human factors, biophysical factors bound agricultural systems. Precipitation, soil conditions, temperature, and water supplies constrain how a farmer uses land, although technology allows alteration of the environmental factors given sufficient knowledge and capital. While not disregarding the importance of biophysical factors, the present research does not analyze them for two reasons. First, as mentioned above, biophysical factors are changeable with the application of technology (Doolittle, 1984; Turner and Brush, 1987). Second, although biophysical factors do limit what crops can be grown where these factors rarely determine a particular crop outcome. In this, we thought of biophysical factors as sufficient conditions for particular cropping outcomes. Without the exploration of social factors, biophysical explanations of cropping approach environmental determinism. Biophysical factors act in concert with social processes (innovation, economies, cultural preferences) to shape cropping outcomes. Invoking the sufficient–necessary divide again, it seemed to us that social factors usually operated as necessary conditions with sufficient conditions on the biophysical side of the relationship (Turner et al., 1993).

2.3. Case selection and coding

This article is based on the analysis of 91 published studies of agricultural land intensification. The study sought to build on the precedent of its companion study on deforestation in both the identification of cases and the coding of variables (Geist and Lambin, 2001). As in the companion study, we selected cases initially from the International Science Index (ISI). For this study we expanded the case universe to include other online data sources and a number of book chapters. While using online data sources provided limitations to the number of possible cases (e.g., no gray literature cases appeared in these sources) it did ensure that all cases read had been peer reviewed. We focused on the tropics under the assumptions that the least understood cases of agricultural intensification occurred there, that a better understanding of how tropical biomes are influenced by people is needed, and numerous tropical ''hotspots'' (Achard and Eva, 1998; Mittermeier et al., 1998) are undergoing rapid change. The case study universe also was restricted to subnational studies. Many of the articles selected presented more than one case, conducting their own comparative analysis of as many as 17 cases (Brown and Podolefsky, 1976). In total, 108 separate instances of agricultural intensification were coded.

Unlike the companion deforestation study, however, the most important variable—the outcome—proved quite problematic, for the reasons discussed above. The study therefore turned to the emerging literature on comparative case study analysis, especially Ragin's (2000) writings on comparative methods. Ragin argues that sample selection flexibility is crucial to the comparative case mode of inquiry, which embraces a continuous dialogue between ideas and evidence. The crux of the matter is the determination of the outcome of interest—the dependent variable. In this respect, the meta-analysis cannot build a control group according to standard practice of statistical analysis, since case studies are rarely published about land change that did not occur (though some cases were identified that sought to understand why land change failed to occur despite the presence of the theoretically sufficient conditions).

In order to retain the information presented on the change in the dependent variable, we decided to track a series of aspects of change in the production system, any of which we deemed sufficient to indicate intensification. These variables included:

- size of landholdings,
- type of land used (e.g., upland, bottom land/swamp),
- production (qualitative),
- production amount (quantitative),
- land intensity, or the frequency with which parcels are cultivated,
- production mix, including cultivars and livestock,
- production techniques (e.g., intercropping),
- mechanical technology,
- chemical technology,
- water management,
- labor,
- other capital requirements.

As noted above, the agricultural change literature provides strong theoretical foundations for hypothesizing the importance of a range of causal factors, both biophysical and human. While a given factor (e.g., precipitation) may be observed to directly cause change in one case (e.g., drought causing the adoption of irrigation), it may function as a general context in others (e.g., interannual variability influencing cropping strategies). Although it may not be found to have triggered a change in a particular case, the state of that factor is an important part of the conditions under which the production system exists and should therefore be retained for comparative purposes. The biophysical variables recorded in this study include:

- biome (rainforest, desert, alpine, etc.),
- topography (general characterization, elevation range, and steepness),
- precipitation (annual means and variability),
- water bodies (presence and proximity),
- soil conditions (fertility, structure, erosion).

We identified over two-dozen human and social variables, which we grouped as follows:

- *Demographic*: Population size, growth, density, distribution, composition (age, gender); settlement/migration.
- *Economic*: Market demand/access.
- *Institutions*: Government/non-government policy or program, property regimes, infrastructure, water program, income-affecting program, off-farm income or food, religion/ethnicity, social structure/standard of living, education.

We recorded information on each independent variable into a database, and subsequently coded as one of the three states based on the importance that the authors ascribed to the variable:

1. An important factor in causing the observed outcome.
2. Not an important factor in causing the observed outcome.
3. Absent (not mentioned).

3. Analysis

A first round of analysis followed the precedent of the companion deforestation study in examining the frequency of occurrence of each variable. This provided a view of the prominence and regional variations of each factor (McConnell and Keys, forthcoming). In the second round of analysis, we searched for patterns in importance of causal variables, what Ragin (2000) termed configurations of conditions, where different conjunctures of causation may be found, as opposed to the standard practice of treating variables as interchangeable factors capable of acting independently, or as "substitutable instances".

In the present study of agricultural change, we queried the database for the frequency of importance of each independent variable—the proportion of cases in which a given variable appeared as an important factor in the observed change in the agricultural system. We then subjected the database to multiple, iterative cross tabulations, which revealed the frequency of occurrence of clusters, or configurations, of variables. This proved unsatisfactory, due in large measure to the high rate of absence of key variables. Finally, we grouped the cases according to a set of non-exclusive land-cover outcomes of interest to the global change community (i.e., change in field crops, horticulture, addition of woody biomass). We examined the cases fitting these outcomes with regard to the associated land-use practices (e.g., use of agrochemicals, alteration of hydrological regimes), as well as the causal and contextual factors.

4. Results

This section describes the results of the analysis, beginning with the agricultural outcomes covered in the cases, and then turning to the causal and contextual factors associated with these outcomes.

4.1. Outcomes

This study revolves around the outcomes of relevance to global environmental change, including changes in

Table 1
Changes in production system, all regions

	Pan-tropical		Africa		Americas		Asia	
Total systems	108	%	39	%	35	%	34	%
Crop mix	71	66	29	74	28	80	14	41
Production	67	62	23	59	29	83	15	44
Land intensity	67	62	26	67	16	46	25	74
Labor inputs	51	47	16	41	23	66	12	35
Chemical inputs	48	44	18	46	13	37	17	50
Water management	46	43	12	31	9	26	25	74
Land holdings	42	39	18	46	18	51	6	18
Techniques	37	34	10	26	10	29	17	50
Mechanical inputs	36	33	11	28	4	11	21	62
Land used	34	31	12	31	14	40	8	24

the nature and duration of crop cover on the land, as well as the chemical and hydrological aspects of the farming systems. We therefore define outcomes in terms of changes in cropping intensity, in shifts to new cultivars, as well as the application of chemical fertilizers and the use of fossil fuel-powered machinery, and the alteration of surface hydrology (Table 1). These dynamics are summarized under the terms of the industrialization of agricultural, conceived as a shift from low-external input systems that largely mimic natural processes and conditions to a high-external input systems involving the import and export of nutrients and energy (agricultural metabolism).

Three major crop cover changes were recorded: increases in the cover frequency of crops (cropping intensity), changes in cultivar grown, and the addition of landesque capital or irrigation works (non-innovative intensification). These categories are not mutually exclusive. Many of the systems studied included more than one of the above noted changes. This complexity is unsurprising given the multiple strategies that land users implement to enhance profits or survival chances. Each category exhibited variation in the extent and impact of the changes noted. These are detailed below. In addition, the change in cultivar category is broken into four separate groups: the production of vegetables (horticulture); the addition or substitution of field crop cultivars; the addition of woody biomass (arboriculture); and the addition of livestock.

4.1.1. Changes in cropping intensity

Perhaps the simplest example of agricultural intensification involves an increase in the time that a given plot is under cultivation (Hayami and Ruttan, 1985; Turner and Doolittle, 1978; Turner et al., 1977). Extensive swidden systems use plots for as little as 1 year and let the plot fallow for as long as 20 years. As the agricultural system intensifies however, that fallow period shortens and the cropping period lengthens. Some intensive agricultural systems have little or no fallow time, experiencing multiple cropping cycles in 1 year. Turner and Ali (1996), e.g., noted that farmers in Bangladesh keep their vegetable and rice plots constantly in use in response to subsistence and commercial demands, yielding up to three crops per year. Increasing the cropping intensity can accompany changing the crop, e.g., the shift from a subsistence grain to vegetables for market. These cases represent innovative intensification, i.e., in addition to increasing the amount of time land is under cultivation the farmer adopts new crops or new techniques (Laney, 2002). Other cases involve increasing cropping intensity while maintaining the same cultivar, representing non-innovative intensification (Laney, 2002). Cropping intensity is important to global environmental change because changes in albedo, ground cover, carbon sequestration potential, and soil erosion are influenced by the amount of time a crop covers the soil.

Of the cases studied, 70 experienced an increase in the intensity of cropping. Nine of these cases represent a change in land intensity only, i.e., no other significant change was noted in the case. Most cases of this type of non-innovative intensification occurred in Africa. Much more frequent, however, are the cases in which cropping intensity increased in concert with new crops or the addition of agricultural technology.

4.1.2. Change in cultivar-cropping emphasis

Farmers adopt new crops or varieties of crops to respond to different demands or when presented with new opportunities. Multiple pathways exist for farmers to encounter and receive new crops, including markets, exchange between farmers, extension programs, and experimentation. Adding new crops often accompanies the addition of agrochemicals and agricultural technology. We identified three broad categories of cultivar-cropping emphasis change: horticulture, field crops, and arboriculture. Sixty-nine involved cultivar change dispersed almost evenly across the three regions. The frequencies of the types of change involved are non-exclusive, i.e., in some cases farmers added coffee cultivation to a system that already mixed raising livestock and gardening.

4.1.2.1. Horticulture. Forty-one of the cases involved adoption of or changes in horticultural practices. Horticulture involves the intense management and care of crops such that each plant is treated as an individual (Wilken, 1987). Horticultural crops are typically non-staple, perishable crops requiring intense attention. Horticulture can densely cover the ground with multi-cropping, and multi-story plantings are common. Turner and Ali (1996) noted that some of the garden plots in Bangladesh are covered in horticultural crops twice per year, i.e., a cropping rate of 200%. Many horticultural systems are extremely intense in terms of labor investments to the land. In general, horticulture denotes the cultivation of vegetable or other high-maintenance crops on small plots. Sixteen instances were found in the sample in which farmers used horticultural techniques exclusively, while 25 more cases featured horticulture in concert with other activities. Keys (2004), e.g., reported that farmers in southern Mexico plant both horticultural crops and field crops during the same growing season on different plots of land.

Changes in horticulture usually involved changes in the use of agricultural technologies. Seventy-five percent of the horticultural cases used agrochemicals to aid cultivation; half of the cases employed water management while 12% used mechanical technology to aid in cultivation. Along with altering the land-cover characteristics of the ground, horticulture also contributes to alterations in the hydrological and biogeochemical cycles. Although small in size, horticulture maintains importance for global change in that it is the main form of agriculture in urban and peri-urban settings. In addition, horticulture greatly benefits household economies by adding much needed cash from sold production.

Indeed, horticulture frequently appears in situations near urban centers that demand vegetables for non-agricultural workers and residents. These local or nearby markets encourage farmers to grow higher-value crops on limited landholdings. Eder (1991) noted that farmers near Cebu City in the Philippines began cultivating new vegetables in response to increased demands and new taste preferences. A number of cases of horticulture also involved markets that lay farther away from cropping regions. Chilies, produced in southern Mexico, e.g., were sold some 1000 km away in Mexico City (Keys, 2004). Some of the horticulture in question exists within the cities that contain vegetable markets. Gumbo and Ndiripo (1996) explained how available land in Harare, Zimbabwe, is cultivated for local markets and exchange.

4.1.2.2. Field crops. The second major category of cropping change observed involved alterations to field crops. There were 27 cases of field crop alteration, 10 of which involved only a change in the field crop, while the remainder also involved changes in other parts of the production systems. Field crops contrast with horticulture and arboriculture in that the entire field, rather than individual plants, is considered for its health and productivity (Wilken, 1987). Field crops are often staple crops (although not always in the case of fiber crops for example) that grow in homogeneous cover. Eighteen cases of field crop change alone occurred within our sample, ranging from high-yielding rice varieties to cotton (Leaf, 1987). These were distributed proportionally throughout the regions. Leaf (1987) noted that farmers in India adopted improved varieties of cotton and wheat to sell in expanded markets. Field crops also can be grown for animal consumption as happened in Guillet's (1987) study of farmers in Peru. Indeed, the increase and intensification in raising livestock was a common co-occurrence with field agriculture. Fisher et al., (2000), e.g., demonstrated that the stabling of cattle led to the field cultivation of forage.

Improved varieties of field crops frequently provide more foodstuffs. These changed crops, however, also challenge farmers. Improved plant species are notorious for increased nutrient and water needs and often require agrochemicals and machinery in order to out-produce native land races. Ninety percent of the field crop alterations noted the application of agrochemicals for fertilization, pest eradication, and weed control. Furthermore, 50% of the field crop alterations entailed mechanical technology, while 40% entailed water management techniques. Thus, although more extensive in spatial organization than horticulture, field agriculture increasingly harnesses chemical, mechanical, and hydrological power to succeed.

Field crop changes occurred within the context of both higher local and higher international demands. Staple crops—rice (Godoy et al., 1997), maize (Humphries, 1993), and millet (Kasfir, 1993), for example—frequently were sold to satisfy growing urban populations in need of relatively cheap foodstuffs. A number of cases involved more expensive luxury items such as tobacco (Barlett, 1976) and cotton (Hopkins, 1987) for distant national and international markets. Unlike horticulture and arboriculture, field crop changes also appeared in a number of cases in which high-yielding varieties of previously grown crops were planted and used. The agro-technologies promise to lead to increased production on similar amounts of land.

There is an important distinction to be made between types of field crops. Roughly, half of the changes in field crops occurred in the context of hybrid subsistence production that maintained a primary dependence on self-provisioning. The other half of the cases represented hybrid subsistence-market dynamics but showed more reliance on marketing agricultural produce. Not surprisingly, this division of cases led to different outcomes. In cases more reliant on self-provisioning fewer inputs were used, resulting in less application of agrochemicals and mechanization. Cases more reliant on the market, however, showed a greater use of Green Revolution technologies and machinery.

4.1.2.3. Arboriculture. Arboriculture is defined here as the planting and maintenance of trees for economic reasons, usually for fruit, fiber, timber, or non-food reasons. Our study included 26 cases of arboriculture: nine stand-alone cases and 17 hybrid cases, of which two had two cases each. Of the arboriculture cases in the sample four appeared in Asia, eight in the Americas, and 12 in Africa. In general, trees are grown for two reasons: for the fruit or fiber they produce or for timber. We found only one case of arboriculture for use as timber—the high-value mahogany tree (Browder and Pedlowski, 2000). Conversely, of the 26 cases of arboriculture, 23 cases involved harvesting from living trees. Arboriculture cases in the sample produced coffee, various fruits, and latex. In some cases, fruit are harvested from existing forests, while in other cases trees are planted with the intention of harvesting some portion of the tree. Brondízio and Siqueira (1997), e.g., described the harvesting of the fruit of the *açai* palm in local forests. While the *açai* harvesters do in fact protect and encourage the growth of the trees, they do not plant the trees. In another case, Browder and Pedlowski (2000) noted that land users adopted tree agriculture that included both fruit and timber components, planting and caring for the trees themselves.

The overwhelming portion of cases in arboriculture points to the proliferation of woody biomass on some agricultural plots, and some of the newly planted trees take the place of more traditional agricultural field or garden crops. Additionally, arboriculture utilizes agricultural chemicals and technology. In the cases where arboriculture was the only land-cover change noted, 78% of the systems were treated with agricultural chemicals and 44% used water management and mechanical technologies.

The addition of trees to cropping systems is notable for both the climate and environmental services that trees provide and because of the ways people are able to combine arboriculture with other economic activities. Non-timber arboriculture concerns two broad types of crops: fruit and stimulant/flavorings. In the cases studied fruit trees, such as the *açai* palm generally served to supply local urban markets with increased demand for luxury crops (Brondízio and Siqueira, 1997). In contrast, vanilla produced in Madagascar (Laney, 2002) was sold wholly on the international market. Coffee cultivation occurred in many cases (Bernard, 1993; Boyd, 2001; Conelly and Chaiken, 2001; Goldman, 1993; Kasfir, 1993; Kull, 1998; Laney, 2002; Okoth-Ogendo and Oucho, 1993; Schelhas, 1996; Taussig, 1978; Tiffen et al., 1994) and was usually exported to international destinations.

4.1.2.4. Non-intensification. Of the 91 cases studied, 15 represented cases of no significant intensification of the cropping system. Indeed, a number of cases exhibited a backward slide, showing signs of disintensification or stagnation. The existence of non-intensified agriculture reminds us that the path to increased inputs and outputs is not given; conditions need to coalesce to allow intensification to occur.

4.2. Causes and contexts of agricultural change

Although agricultural intensification took different forms, from increased land intensity to changes in the types of crops cultivated, it is important to consider what factors enabled the changes to take place. Indeed, the major variables commonly identified—market dynamics, government policies, and social relationships—seem to operate in favor of and against agricultural intensification depending on the presence or absence of mitigating factors. The ability of multiple case studies to include a wide range of factors and outcomes of change enriches our understanding of the Earth system, one of the primary goals of global change science. To add to our understanding of the Earth system we analyzed the ways that social and biophysical factors combine to shape tropical agricultural intensification.

4.2.1. Biophysical factors

During the course of this comparative analysis the dearth of biophysical information in published case studies surprised us (Table 2). Almost one-third of the cases could not be coded for basic precipitation categories (humid, sub-humid, semi-arid, arid). Information on soil properties lacked as well in more than one-third of the cases and, when provided, often was cursory, rarely referring, e.g., to a recognized pedological system. While general topographic information was more frequently provided, many studies lacked elevation or slope values. Most likely researchers gathered information that they did not report, due either to limitations on the length of articles in peer-reviewed

Table 2
Biophysical contexts of agricultural change

	Important	Not important	Absent	Total
Precipitation variation	30	30	48	108
Watercourse/water body	23	35	50	108
Soil properties	43	27	38	108

journals, or to the perceived unimportance of biophysical factors. Either way, the lack of information, and its inconsistency when provided, precludes systematic analysis of the role of biophysical context in the process of agricultural change.

4.2.2. Demographic factors

Probably the most widely studied causal factor in the agricultural change literature is population growth. The reviewed cases follow this trend, though we were surprised to find a dozen cases providing no demographic information (Table 3). In an additional 21 cases, population size, growth, or distribution was mentioned but not considered an important factor in the intensification process described. A great many of the authors acknowledge Boserupian theoretical foundations in their studies (Benin and Pender, 2001; Benjaminsen, 2001; Goldman, 1993; Guyer and Lambin, 1993; Kull, 1998; Kunstadter, 1987; Laney, 2002; Shidong et al., 2001a, b in Tri-Academy), and some explicitly set out to resolve the dispute about the effect of population growth on agricultural production (Barlett, 1976; Shorr, 2001; Tiffen et al., 1994; Turner and Ali, 1996). Echoing the results of the companion study on the causes of tropical deforestation (Geist and Lambin, 2001), our study found population size, growth, and density virtually never work in isolation; rather, other social and economic factors mediate between population attributes and agricultural systems. In one notable case (Barlett, 1976), population growth appears to have been the single factor responsible for the addition of tobacco production on terraces to the pre-existing swidden milpa system. The case, however, provided no information on government or NGO programs, or new market demand, which might be expected to play a role in the production, processing, and marketing of tobacco.

Table 3
Noted importance in case study

Variable	Important	Not important	Absent	Total
Population variable				
Population numbers/density	70	22	16	108
Settlement/migration	34	41	33	108
Population structure	8	12	88	108
Institutional variable				
Market demand	69	11	28	108
Market access	58	18	32	108
Property regime	65	34	9	108
Government/NGO policy	55	24	29	108
Income-affecting program	36	14	58	108
Infrastructure program	33	10	65	108
Water-provision program	16	0	92	108
Standard of living	48	32	28	108
Off-farm employment	30	28	50	108
Education	21	11	76	108
Religion/ethnicity	7	41	60	108

Cases in which population size, growth, and distribution were deemed by the authors not to have played important roles were found for each of the outcomes, usually in small numbers. The exception was in cases of changes in field cropping systems, where two articles (Godoy et al., 1997; Shively, 2001) provided multiple cases and concluded that market and related government extension programs were important, while population factors were not.

We noted another set of demographic factors and described them under the rubric of settlement and migration. While infrequently cited, migration and settlement proved crucial, especially in the adoption of tree crops. Several cases concerned large-scale migrations or resettlements associated with the establishment of plantations (Schelhas, 1996), the construction of roads (Conelly, 1992), or political events (Kasfir, 1993). The rest of the cases concerned temporary, permanent, or circular wage labor migration. Two cases, Tiffen et al. (1994) and Boyd (2001), concerned the return of populations to rural areas at the end of a lifetime migration pattern.

4.2.3. Market influences

Agricultural change theories frequently posit the market as an important cause of agricultural intensification. How the market is operationalized differs widely within these theories but is seen to encourage change as the incentives to participate in the market outweigh the benefits of non-participation. In this analysis, we considered market access and market demand separately, although often linked, factors. Market access denoted that in some way—transportation, policy, or otherwise—farmers had gained the ability to participate in a market previously denied to them. Market demand on the other hand denoted either a growth in an existing market or demand for products not previously sold. Clearly these variables could be confounded, as access does represent new demand in a sense, although grouping the two together overshadows market liberalization, road building, and other factors that can enhance market performance.

Market dynamics operated in nearly all of the analyzed cases of agricultural intensification (Table 3). Sixteen cases reported no information on market dynamics, while one case cited a failed market as the reason for agricultural disintensification (Humphries, 1993) (Table 4). Case studies reported on market demand for the destination of the crops grown, including international markets, national markets, urban markets, and local rural markets. Nearby urban demands for crops played strong roles in horticultural

Table 4
Market access/demand as a causal variable

	International	National	Local urban	Failed	Local rural	Absent
Field crop	2	13	0	0	0	5
Horticulture–field crop combination	1	3	10	0	0	1
Arboriculture	4	2	1	0	0	1
Non-innovative intensification	0	9	0	0	1	4
Arboriculture combination	8	9	6	1	0	2
Non-intensification	3	5	1	0	0	3

cases, appearing in almost all cases of pure horticultural change. The pull of urban markets for horticultural products is unsurprising. Horticultural crops were generally vegetables and fruits and, given the perishability of these crops, could not be transported long distances without refrigeration, often lacking in the developing tropics. Similarly, arboriculture exhibited a strong market demand component albeit for a wider international market, although it also showed strong influence in national and urban markets when it was a mixed system in combination with horticulture. Many of the cases reported development of coffee or vanilla that was destined for international purchase. The field-cropland combined class gives no clear signal of market demand's importance, possibly linked to farmers only recently entering into market structures and thus not yet exhibiting strong market ties. Where field crop cases did report a strong market pull farmers sold to a national rather than purely local, market.

4.2.4. *Institutional factors*

We posited several institutional forms as potential actors in enabling or constraining land use, and thus land-cover change, including government and non-government investment in infrastructure and subsidies, and property regime and allocation.

4.2.5. *Government and non-governmental influences*

A wide range of policies, programs, and fiscal considerations directly or indirectly affect farmers. More than half of the case studies mentioned government and non-government organization activities. We tracked several specific types of activities, including income-affecting programs, water-provisioning programs, and infrastructure programs. Income-affecting policies included both the addition and withdrawal of subsidies, price supports, and taxation. Water-provisioning programs included the construction of levies, dams, and irrigation canals in addition to tube wells, while infrastructure included programs that provided rural electrification, road construction, and stabling. A final category included extension services, neoliberal restructuring policies, conservation, and cooperative programs.

In 25 cases, subsidies given to farmers influenced the agricultural change recorded (Table 5). Subsidies typically were granted to farmers for the purchase of agricultural chemicals or as government-controlled prices that allowed farmers to earn income that enabled them to intensify their agriculture. Indeed, the provision of subsidy seems to have an important effect on agricultural intensification. Price controls and taxation, potentially seen as negative subsidies, appeared but were not a strong influence. This is unsurprising, since programs that draw down the economic resources of farmers should limit intensification and would thus largely go unreported in the universe of case studies that we sampled.

Because intensification frequently involves keeping land in crops during potentially dry seasons of the year and high-yielding varieties often demand water inputs, we expected that water-provisioning programs would feature prominently. However, water programs were absent in all but 11 of the coded cases (Table 6). Where water programs did exist they generally were in the form of wells, dams, and irrigation infrastructure. The lacuna of irrigation may be in part explained by the many cases of intensification that occurred in physical environments that are difficult to irrigate. In southern Mexico, e.g., there is no usable ground or surface water within a reasonable distance from the fields that farmers cultivate (Keys, 2004).

Road infrastructure appeared in 26 cases but did not give a clear signal in terms of how change would take place. For example, seven field crop cases showed the influence of roads in the change noted in Table 7, while roads appeared in six of the cases of non-intensification. This finding supports Angelsen and Kaimowitz's (1999) assertion that without necessary inputs, roads are insufficient alone to cause agricultural change. Other instances of infrastructure included electrification, stabling, and the construction of rail lines. These tended to be individual cases and did not appear with sufficient frequency to permit the formulation of conclusions.

Extension services appeared in 27 of our cases with nine of them being represented in the pure field crop change category. In general, this involved the provision of information and materials for new varieties of crops.

Table 5
Income-affecting programs

Outcome	Subsidy	Price control for cheap urban foods	Devaluation of currency	Price control in farmer's favor	Withdrawal of subsidy	Increased taxation	Absent
Field crop	7	1	1	0	0	0	11
Horticulture–field crop combination	4	0	0	1	0	0	8
Arboriculture	1	1	0	0	0	0	6
Non-innovative intensification	7	0	0	0	1	0	8
Arboriculture combination	6	0	1	1	0	2	9
Non-intensification	0	0	0	0	0	0	12

Table 6
Water-provisioning programs

	Well installation	Irrigation	Levy	Dam	Failed	Absent
Field crop	2	1	0	0	0	17
Horticulture–field crop combination	1	3	2	0	0	9
Arboriculture	0	0	0	0	0	8
Non-innovative intensification	0	0	0	1	0	15
Arboriculture combination	1	0	0	0	1	17
Non-intensification	0	0	0	0	0	12

Table 7
NGO/government programs

	Neoliberal adjustments	Extension program	Conservation	Cooperative	Ineffective cooperative	Colonization	Absent
Field crop	6	9	1	1	0	0	3
Horticulture–field crop combination	2	2	2	1	0	0	8
Arboriculture	2	1	0	1	0	0	3
Non-innovative intensification	0	5	1	0	0	1	8
Arboriculture combination	4	7	1	2	0	0	11
Non-intensification	2	3	0	0	1	0	6

Neoliberalism appeared in 16 cases and generally included structural adjustment programs that affected the ways markets functioned. Conservation policies provided some extension and also limited the land that people farmed by denying them access to land and were often cited as a land constraint. Cooperative programs often included marketing and extension services and appeared in a total of five cases.

4.2.6. *Property regime*

Property regimes include both ownership (communal and private), as well as processes or exchange, consolidation, exclusion, and other forms of unequal access (e.g., by gender, by ethnicity). Some information on property regimes was almost universally supplied, being absent in only eight cases. However, property regime was infrequently considered a key factor in the intensification process, particularly concerning field crops and horticulture. Furthermore, change in these two categories was associated with a broad range of property regime factors. Six cases showed that farmers, particularly in Africa, can meet production demands without intensifying when they have access to communal land or are able to borrow or rent land (Laney, 2002; Richards, 1987).

Property regime factors, especially processes of privatization and exclusion of certain groups, were important in the adoption of tree crops and in taking advantage of market opportunities. For example, the shift to orchard crops in the highlands of Madagascar

(Kull, 1998) occurred under circumstances wherein landless peasants undertook sharecropping for absentee landlords. Land reform was mentioned in a modest number of cases, appearing strongly in the frequency of intensification outcome, especially in cases from Peru (Bebbington, 2000; Coomes et al., 2000).

Fig. 1 demonstrates an analysis of major, conventional causes of agricultural change and the frequency with which they appear in this review of 91 cases studies and combined case studies. Perhaps unsurprisingly the variables commonly postulated to drive change, the market, population and policy feature prominently in the case studies analyzed. The following section discusses the implications of the predominance of conventional explanations of agricultural change in the tropics.

5. Discussion, conclusions, and recommendations

This review of agricultural change literature reveals that the term encompasses several processes of interest to the global change community. The processes of interest vary: researchers interested in closing carbon budgets may be primarily interested in the addition of woody biomass to agricultural lands and in changing soil respiration; researchers interested in nutrients, hydrology, or other dynamics may be interested in changes in field crop mixtures and cropping intensities; and researchers interested in social outcomes may focus on the output of food and fiber, the use of purchased inputs, and the sale of produce. A single definition of "intensification" thus proves elusive, and probably the best that can be hoped for is that studies are sufficiently robust in their data collection and presentation to be applicable to more than a narrowly defined set of analyses. Likewise, the enumeration of the conditions under which agricultural change takes place must endeavor to account for a broad set of factors. The lack of biophysical information, in particular, is a serious obstacle to comparative analysis.

While the cases reviewed here covered a wide range of dynamics, the main processes of intensification captured were the adoption of new field crops, the planting of trees, and the development of horticulture. The main factors associated with these processes are demographic, market, and institutions, especially property regimes. These factors are difficult to separate analytically, as when growing urban populations express their demand through markets.

Like the companion study on tropical deforestation, population "pressure" does not work in an unmediated fashion; rather it operates in conjunction with market and other social forces. Conversely, population pressure does not always lead to intensification, as farm families employ strategies such as borrowing land, or temporary or permanent migration. In some cases other factors, such as markets or government programs, trigger changes, making underlying population dynamics appear less important. While cases can be found that illustrate a Malthusian degradation spiral associated with increasing population, it is not difficult to find cases illustrating constructive outcomes. In effect, no community is in perfect demographic equilibrium, and the number and ability of productive members, and their ratio to consumers, as well as the needs and aspirations of those consumers, are always important factors. It is crucial that future studies account not only for internal ("natural") demographic growth, but also for seasonal, generational, and permanent flows of labor and consumers, and to the knowledge, skills, and other resources carried with immigrants and return migrants.

Likewise, virtually no totally isolated agricultural communities exist in the world today. Outsiders express their demands for agricultural products nearly everywhere, and market signals are pervasive, influencing a broad range of outcomes. While proximate urban markets are seen to encourage the development of gardening and fruit production, distant international markets provide the incentive for planting other tree crops, particularly stimulants such as coffee, tea, and cocoa. The vagaries of the demand for these products have important implications for the production of crops that take several years to produce fruit.

At the same time, the production of tree crops has important implications for land tenure. In most places, planting and caring for trees implies or provides secure access to the land. Moreover, access to communally held land resources often enabled communities to meet changing demands without a shift in the techno-managerial regime. The common property literature suggests that privatization is far from a panacea for sustainable forest management—on either ecological or social grounds—and the present review finds similar evidence in agricultural systems (McKean, 2000; Ostrom, 1990). While some cases mentioned a shift from communal to private control of land, certain groups or individuals through land consolidation and related processes of exclusion often captured the benefits of that shift. Interestingly, land reform, even when mentioned, rarely operated as a key factor in intensification.

Perhaps more than anything else, this meta-analysis demonstrates the importance of accounting for a broad range of institutional factors in addition to property regimes. Government and NGO programs come in myriad forms, and the cases reveal both their intended and unintended consequences. With regard to the above discussion on market demand, national-scale fiscal and monetary policy influenced intensification processes, as did the provision of services, including information, financing, and infrastructure.

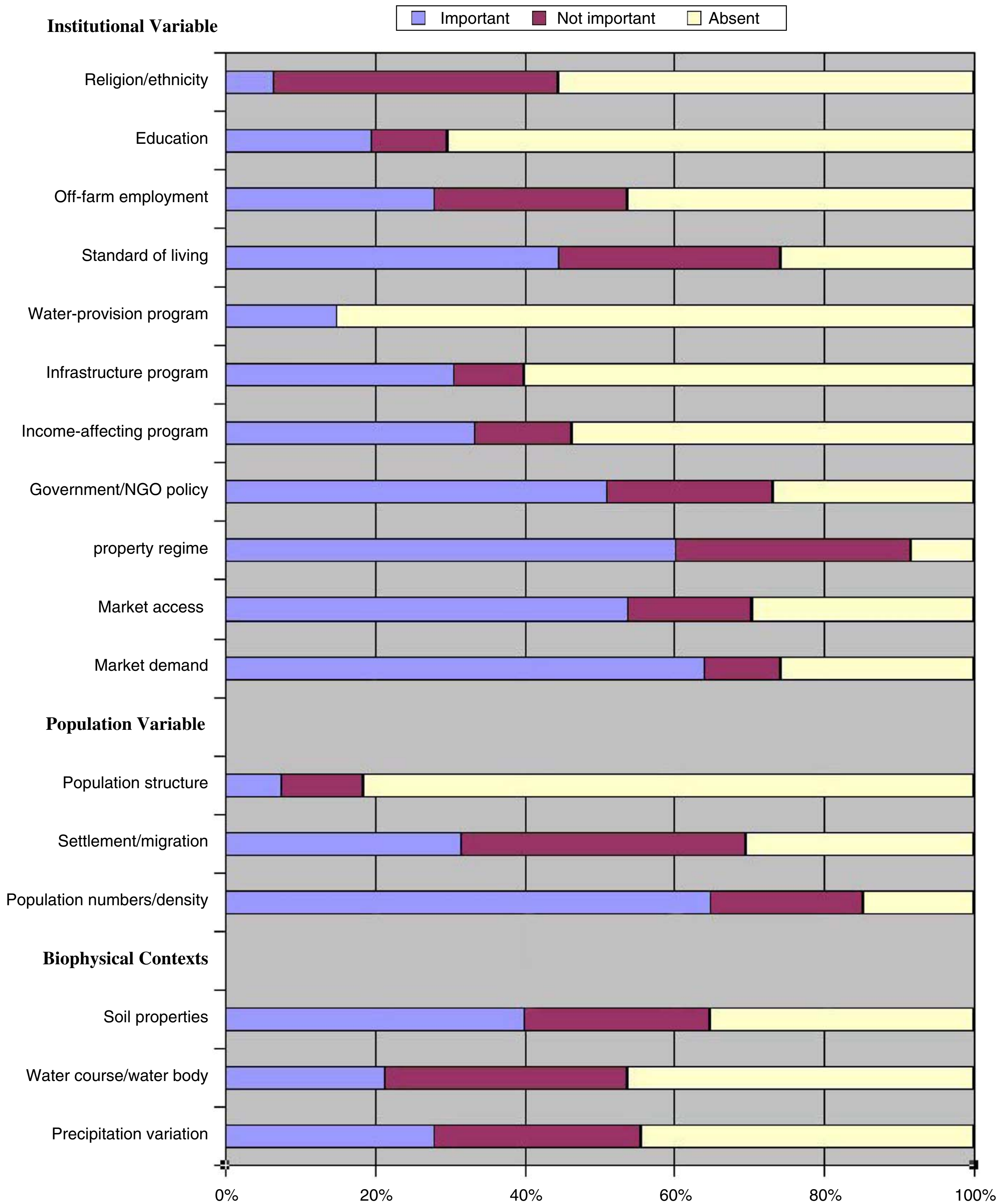

Fig. 1. Compiled causes of change featured in the analyzed studies.

Probably the most important conclusion from this analysis is that the lack of standardization is a significant obstacle to comparative analysis or synthesis. In order to be able to contribute to a synthesis of agricultural change, future studies should address the factors outlined above. Optimally, rigorous comparison and synthesis depends on the collection of standardized sets of information in a coherent way. Prior ex ante comparative efforts (Brown and Podolefsky, 1976; Kasperson et al., 1995; NRC, 2001; Turner and Brush, 1987; Turner et al., 1993) have shown the way. These questions will be within the remit of the new Global Land Project, which will carry forward with the prior efforts of LUCC and its sister project on Global Change and Terrestrial Ecosystems. A cornerstone of the GLP's Science Plan (IGBP, in press) is comparative analyses using consistently defined variables. We hope the research presented here can contribute to the fulfillment of that agenda.

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Appendix A

Cases used in the meta-analysis of agricultural change in the tropics

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