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Land Cover Change and Soil Fertility Decline in Tropical Regions

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Abstract: Land cover changes influence the biogeochemistry, hydrology, and climate of the earth. Studies that assessed land cover changes at the global scale mostly focused on: deforestation, cropland expansion, dry land degradation, urbanisation, pasture expansion, and agricultural intensification. For the assessment, remotely sensed land-cover data, census data, and expert knowledge were used. In tropical regions, forest is cleared for the expansion of cropland, wood extraction, or infrastructure expansion. This widely occurs in the Amazon region and in Asia. In many temperate regions, the area under forest is increasing although forest plantations are also on the increase in the tropics. Croplands expanded by 50% during the 20th century, from roughly 1200 million ha in 1900 to 1800 million ha in 1990. It appears that there is no major desertification in the Sahel region and that urbanisation and most highly-populated cities are found in tropical regions. In China, the area under cropland increased from 98 to 130 million ha between 1949 and 1996. In the same period the area under forest almost doubled. In temperate regions, agricultural land is being taken out of production (set-aside), planted with biofuel crops or converted to recreational or building areas. Some areas appear to be more affected by rapid land-cover change because they are studied more intensively. There are several interacting drivers for land cover change but the exponential growth in human population is important. Currently, 95% of the population growth takes place in tropical regions. Soil fertility in tropical regions is affected by rapid land cover changes. The effects of deforestation and grassland conversions as well as agricultural intensification have been fairly well-documented. The spatial and temporal effects of soil fertility change and its interaction with land cover change remains to be investigated.

Key Words: Land use change, tropical regions, soil fertility, China, deforestation, cropland

Introduction

Human activity affects land cover and land use. Land cover is the biophysical state of the earth's surface and immediate subsurface (biota, soil, topography, surface and groundwater, human structures), whereas land use involves the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation for which the land is used (Lambin et al., 2003). Historically, the driving force for most land use changes is population growth (Ramankutty et al., 2002b) although there are several other interacting factors involved and rates of deforestation and population growth are not linear (Lambin et al., 2001; Lambin et al., 2003). During the 20th century, the world population more than doubled from about 1.5 billion in 1900 to 5.2 billion in 1990. Currently, the world population is growing by 1.3% per year compared to 2.0% growth in the late 1960s. More than 90% of the population growth takes place in tropical regions. About 80% of the population lives in developing regions; Asia accounts for 61% of the world total. The rate of population growth is declining and population will reach around 8.9 billion in 2050 (Lutz et al., 2001).

Land in tropical regions is being used for the same reasons as in temperate regions, namely to grow trees, crops, and animals for food, as building sites for houses and roads, or for recreational purposes. Part of the land in the tropics is being used by smallholders who farm for subsistence. Smallholder agriculture is differently practised in different parts of the world but it has the following characteristics: small-scale, subsistence or semi-subsistence with little or no external inputs, low level of mechanisation, and relatively low yields. Farm sizes largely depend on the intensity of the farming system

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which, amongst others, is determined by both population pressure and agro-ecological conditions. With rapid population growth and in the absence of agricultural intensification, smallholders require more land to grow crops and earn a living; it results in deforestation and land use conversions from grassland to cropland. Such conversions also take place because of the expansion of the area under cash crops (e.g. oil palm and soybean) in the Amazon basin, the Argentinean pampas and in several countries in SE Asia.

There is an increase in the area under forestry plantation in the tropics although accurate data on reforestation are scarce (Lepers et al., 2005). Forestry statistics show that in 1965 there was about 6.7 million ha of forest plantations, in 1980 20.9 million ha, and the total area for 1990 was estimated to be 42.6 million ha (Evans, 1992). Brown et al. (1997) estimated the total plantation area in the tropics to be 44 million in 1990. In China, 1.1 million ha and in India 1.5 million ha of new forest plantations were established in 2000 according to FAO data (Lepers et al., 2005).

Despite enormous advances in remote sensing and GIS technologies in the past decades, systematic examination of trends in terrestrial land cover is yet to be made (Lepers et al., 2005). Most analyses of land-cover changes are based on data from remote sensing, censuses (statistical inventory, national and regional), and expert opinion through formal procedures. In order to integrate these heterogeneous data sources there is a need to determine the interrelationships between the data types (Lepers et al., 2005). There is a need to understand land cover changes and its effect on the overall ecosystems. Land use change affects the global climate via the carbon cycle, the water cycle through changing evapotranspiration and hydrological regimes but land use change also affects biotic diversity, soil degradation, and the ability of biological systems to support human needs. In other words, such changes influences earth system functioning (Lambin et al., 2003).

We know roughly where land use changes occur and we also know that land use changes affect soil chemical and physical properties. Such changes have been fairly well-documented but a systematic global scale link between land cover change and soil fertility change has - to our knowledge - not been made. Here we review the major patterns in land use and land cover change in the tropical regions, including China being the most populated country where in the past decade fast economic growth has influenced land use. Successively, we discuss the patterns in land cover change in relation to soil fertility and nutrient management.

Land Cover Change

Changes in land cover – the global picture

The number of studies on global land use and land cover change is limited. Recent major studies are summarised in this section; they are partly overlapping but present some consensus on the main patterns and directions of global land use and land cover change (Ramankutty and Foley, 1998; Ramankutty and Foley, 1999; Ramankutty et al., 2002a; Ramankutty et al., 2002b; Lambin et al., 2003; Leff et al., 2004; Lepers et al., 2005). In these studies, the following land cover categories are considered as proxy variables for change (Lepers et al., 2005):

1. Cropland expansion and abandonment
2. Forest-cover changes
3. Degrading lands in the dry zones
4. Urban settlements.

Lambin et al. (2003) used 5 categories of land cover change: cropland, agricultural intensification, tropical deforestation, pasture expansion, and urbanisation. Throughout this review, we shall more or less follow these categories to discuss trends in land cover change and its implications for soil fertility and its management.

Lambin et al. (2003) summarised recent estimates on land cover changes. The area of cropland has increased from an estimated 300-400 million ha in 1700, to 1500-1800 million ha in 1990 (Table 1). The area under pasture increased from 500 million ha in 1700 to 3100 million ha in 1990. These increases led to the clearing of forests and the transformation of natural grasslands, steppes, and savannas. Forest area decreased from 5000-6200 million ha in 1700 to 4300-5300 million ha in 1990. The area under steppes, savannas, and grasslands declined from around 3200 million ha in 1700 to 1800-2700 million ha in 1990 (Lambin et al., 2003).

The analysis presented by Lambin et al. (2003) was, amongst others, based on the work of the Center for Sustainability and the Global Environment (SAGE), which produced a series of papers on land cover change

Table 1. Historical changes in global land use/cover between 1700 and 1990. From: Lambin et al. (2003) based on Ramankutty et al. (2002b).

	Land cover in million ha			
	Forest/woodland	Steppe/savannah/grassland	Cropland	Pasture
1700	5000 to 6200	3200	300 to 400	400 to 500
1990	4300 to 5300	1800 to 2700	1500 to 1800	3100 to 3300

(Ramankutty and Foley, 1998; Ramankutty and Foley, 1999; Ramankutty et al., 2002a; Ramankutty et al., 2002b; Leff et al., 2004). Ramankutty and Foley (1999) used a new technique for documenting and monitoring cropland areas by combining satellite-based land-cover images (IGBP 1-km dataset) with agricultural census data. They reconstructed (back-casted) a historical, geographically explicit dataset of cropland areas for the entire globe by statistically combining the 1990s croplands dataset with historical cropland census data.

The area under croplands increased by 50% in the 20th century from 1200 million ha in 1900 to 1800 million ha in 1990. This net increase in cropland area includes the abandonment of 222 million ha of cropland since 1900. There has been greater expansion of cropland areas since World War II than in the 18th and early 19th centuries combined. Significant changes in cropland occurred in South-east Brazil. Cropland expansion slowed down in the Midwestern USA, while there was abandonment in the eastern part. Cropland areas in northern Europe, the former Soviet Union, and China stabilized, and even decreased in some regions, while it intensified in northeast China. Some croplands were abandoned in Japan. Clearing for cultivation continued in South-east Asia and Oceania (Ramankutty et al., 2002b).

Eastern Europe is the most extensively cultivated region in the world, with more than half its land area in crop-cover. However, in absolute terms, the former Soviet Union has the largest cropland area (Ramankutty et al., 2002b). As a percentage of total land area, the greatest cropland expansion occurred in South Asia and South-east Asia - about 11% and 18% of their total land area, respectively, was cleared for cultivation during the 20th century. In these regions, cropland increases matched growing human population. Most regions with high populations have large cropland areas. The nature of this relationship has not changed over the 20th century because it is the greater demand from growing populations that has led to cropland expansion (Ramankutty et al., 2002b). Developed countries such as the USA and the former Soviet Union, with roughly 10% to 13% of the world population, contain nearly a third of the global cropland area. On the other hand, the populous and poorer nations of the world such as China, Mongolia, N. Korea, and South Asia, with roughly 45% of the global population, have only a quarter to a third of the global cropland area.

Lepers et al. (2005) synthesised information on rapid land-cover change for the period 1981-2000 as part of the Millennium Ecosystem Assessment. The synthesis was beset with methodological challenges varying from a range of definitions for land-cover classes to uneven spatial density of information. For example, the authors found that there are no spatial data sets on afforestation and reforestation or on changes in pastures at a regional-to-global scale. Also, more than 90 different definitions of forest are in use throughout the world which makes comparisons and integration of national and regional datasets complex. Despite these challenges, they produced a series of global maps (10 by 10 km grid) that show how land cover has changed in the past decades. Some parts of the world were covered by several data sets, whereas for others only national statistics were available. As a result, some areas appear to be more affected by rapid land-cover change because they are studied more intensively (Lepers et al., 2005). The main changes in forest cover and cropland is given in Figures 1 and 2.

A summary of their findings: in Asia there are many areas where land-cover changes occur most rapidly; the Amazon basin is a hotspot of tropical deforestation and it

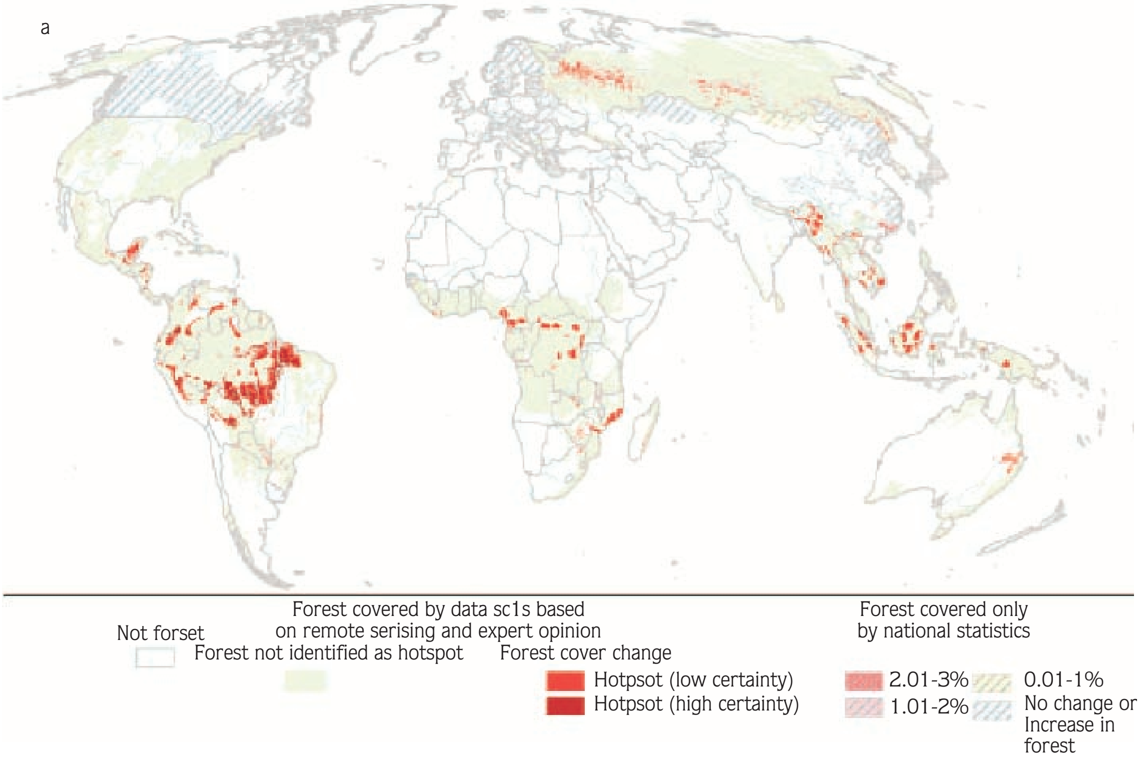

Figure 1. Main area of forest-cover changes between 1980 and 2000. From Lepers et al. (2005).

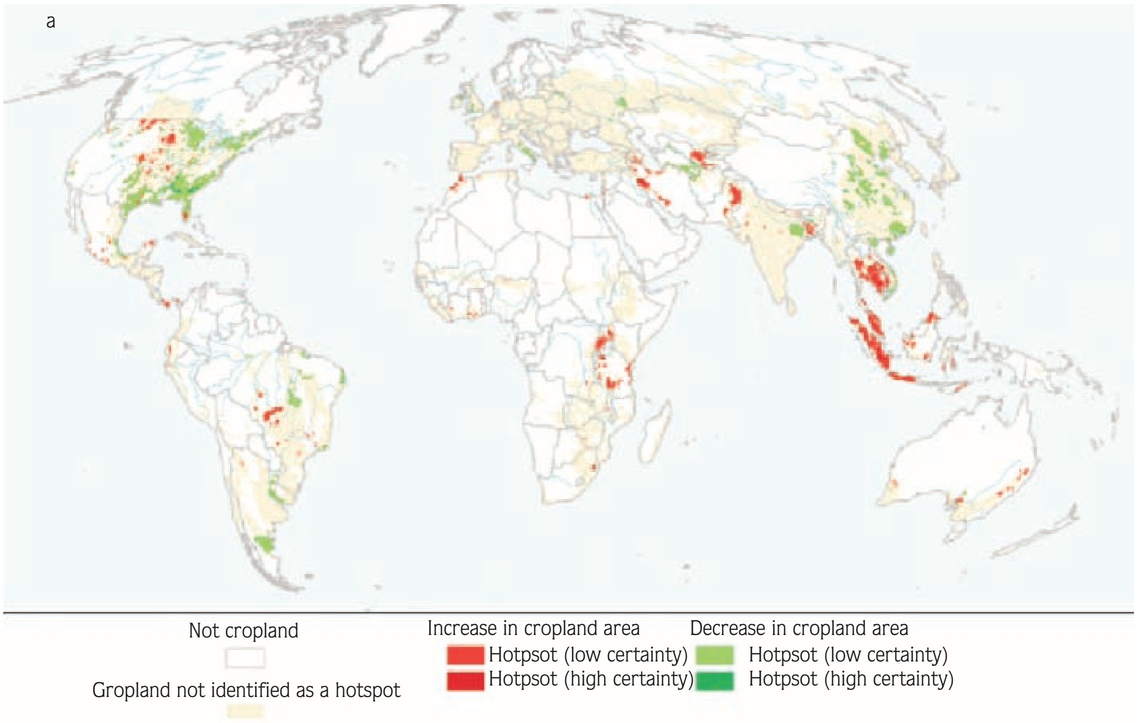

Figure 2. Main area change in cropland extent between 1980 and 1990. From Lepers et al. (2005).

mostly takes place at the edge of large forest areas and along major transportation networks. Deforestation occurs when forest is converted to another land cover or when tree canopy is reduced to less than 10%. Achard et al. (2002) estimated the mean annual change of humid tropical forest between 1990 and 1997. Globally about 5.8 million ha is deforested each year, whereas annual forest regrowth is estimated to be 1 million ha (Table 2). In tropical regions, forest is cleared for the expansion of cropland, wood extraction or infrastructure expansion (Geist and Lambin, 2002).

Lepers et al. (2005) also showed that rapid land-cover changes are not randomly or uniformly distributed but occurs in some locations. Cropland increases coupled to large-scale deforestation occur throughout Southeast Asia. In Siberia, forest degradation is increasing and results from logging activities. In the south-eastern United States and eastern China the area under cropland is decreasing rapidly. It appeared that there is no major desertification in the Sahel region, and that many of the most highly-populated cities are found in tropical regions (Lepers et al., 2005).

Changes in land use in the tropical regions – case studies

In the tropical regions, land cover changes have been assessed used photographs and satellite images, and various examples of such case studies are reviewed below. Examples are given of deforestation, cropland and pasture expansion, and urbanisation. Some studies on land cover change have used expert knowledge (e.g. oral history, narratives) and examples of such studies are Conte (1999), Endfield and O'Hara (1999) or Jones (1999). Although they may gain insight in the drivers of land use change (what make people move) they are no further considered here.

On the ground photographs - Africa

One of the first studies on soils and vegetation changes in Africa was conducted in the early 1920s (Shantz and Marbut, 1923). Shantz and Marbut toured from Cairo to Capetown and took about 5000 photographs. In 1956 and 1957, a large number of sites was revisited and pictures were taken at approximately the same time of the year enabling some assessment of vegetation and land use changes (Shantz and Turner, 1958). In the desert grasslands of South Africa and Kenya, succulent bushes and thorny shrubs had increased at the expense of grasses; in the dry forest clearing and burning had transformed woodland into savannah, whereas rain forest was transformed into high grass and low tree savannah. It was concluded that the increase of human population had placed a great strain on the more productive lands and sub marginal areas had been taken into cultivation (Shantz and Turner, 1958).

A similar approach was taken by Tiffen et al. (1994) who explored the relationship between increasing population density, productivity, and environmental degradation, through a case study of Machakos District in Kenya, over the period 1930 to 1990. They showed that, despite a 5-fold increase in population, the environment in 1990 was much better condition compared to the 1930s (Tiffen et al., 1994). Due to off-farm income, farmers in Machakos could improve the land (Laegreid et al., 1999). Similar conclusions were derived from a study on increasing population density and the availability of land resources in Sukumuland in Tanzania (Meertens et al., 1996).

Table 2. Mean annual change estimates of humid tropical forest cover between 1990 to 1997. Modified from Achard et al. (2002).

	Forest cover in 1990	Annual net cover change		Annual deforestation		Annual forest regrowth		Annual forest degradation	
	Million ha	Million ha	%	Million ha	%	Million ha	%	Million ha	%
Latin America	669	-2.2	0.33	2.5	0.38	0.28	0.04	0.83	0.13
Africa	198	-0.71	0.36	0.85	0.43	0.14	0.07	0.39	0.21
Southeast Asia	283	-2.0	0.71	2.5	0.91	0.53	0.19	1.1	0.42
Global	1150	-4.9	0.43	5.8	0.52	1.0	0.08	2.3	0.2

These studies show what is happening on the ground – they are not quantitative in a spatial sense but depict whether the area under crops, forest or grass has changed. If the time span between the photographs is substantial (< 10 yr), such qualitative observations are useful. They are sometimes contrary to people's perception.

Aerial photographs and satellite images

Several studies on land use changes used aerial photographs or satellite images from different periods combined with Geographic Information Systems (GIS). Holmgren et al. (1994) surveyed woody biomass on farmland in Kenya using aerial photographs and field measurements. A rapid increase of planted woody biomass was observed between 1986 and 1992 and the annual increase was estimated to be almost 5%. Population density was positively correlated with the volume of planted woody biomass: more people, more trees. The results imply that some pessimistic opinions on land-use development in Kenya are incorrect (Holmgren et al., 1994) and confirm some of the observations by Tiffen et al. (1994).

A study in Tanzania using normalized difference vegetation index (NDVI) imagery showed that the overall greenness increased between 1982 and 1994 (Pelkey et al., 2000). Woodland and forest pixels increased in greenness but swamp pixels showed a decline in vegetative cover. A detailed study in the Usambara Mountains in Tanga Region, Tanzania, showed a drastic reduction in forest cover from 53,000 ha in 1965 to 30,000 ha in 1991 (Kaoneka and Solberg, 1994). About one-third of the natural forest was converted to forest plantations. The main cause for the deforestation was the expansion of farmlands and settlements because of population increase (Kaoneka and Solberg, 1994). Several studies from Kenya arrived at the same conclusions. In Embu region, Imbernon (1999b) studied change in land-use in semi-arid and humid areas of Mount Kenya; tree cover decreased from 26% in 1956 to 24% in 1995. The extent of perennial crops (tea, coffee) increased from 1% to 33% over the same period. Bush land, which covered about one-quarter of the area in 1958, was no longer existing by 1995 (Imbernon, 1999b). In the highlands north of Nairobi, Ovuka (2000) observed that in 1960 there was 15% fallow land but this decreased to 6% in 1996. Woodlots had increased from 1 to 3% and coffee gardens from 0.2% to 12% over the same period. Areas without soil and water conservation practises increased from about 25% in 1960 to 70% in 1996. Most farmers depended on income from the land and thought that livelihood was better in 1996 compared to 1960 (Ovuka, 2000).

A study in Lake Malawi National Park, Malawi, using aerial photographs showed conversion of closed *miombo* to sparse woodlands (Abbot and Homewood, 1999). Between 1982 and 1990, closed canopy woodland decreased by 7% whereas sparse woodland increased by 342%. The human population more than doubled between 1977 and 1992 and the authors consider increased fuel wood harvesting the main cause for the decline in *miombo* woodland (Abbot and Homewood, 1999). In south-western Burkina Faso, Gray (1999) showed that between 1981 and 1993 the area under cultivation roughly doubled at the expense of scrub savannah. Human population doubled between 1971 and 1985.

Tekle and Hedlund (2000) compared aerial photographs from 1958 and 1986 in the highlands of Kalu District, Ethiopia. A decrease in coverage by shrublands, riverine vegetation, and forests was observed. Areas under cultivation remained more or less unchanged. It was concluded that land cover changes were the result of clearing of vegetation for fuel wood and grazing.

Lumbanraja et al. (1998) and Syam et al. (1997) described changes in land-use in West Lampung (South Sumatra). Between 1970 and 1990, the area under primary forest decreased from 57% to 13%. In 1970, 9% of the area was under slash-and-burn agriculture but in 1990 there was no land under shifting cultivation left. Lowland coffee plantations were absent in 1970 but occupied 40% in West Lampung in 1990. In North Lampung, Imbernon (1999a) described land-use changes between 1930 and 1996. Dense forest covered about 80% of the area in 1930, but no more forest was left in 1996. Most changes occurred between 1969 and 1985, following the transmigration programme and the development of agricultural plantations.

In densely populated Java, which had a long history of population pressure causing agricultural land use to expand and intensify, much of the prime agricultural land is converted into residential and industrial areas (Verburg et al., 1999). This is a major factor affecting food production in rapidly growing areas which will influence the production capacity of existing agricultural areas and occurs in many parts of the world (Lambin et al., 2003).

In the hillside region of central Honduras it was found that forest cover was reduced from 56% in 1955 to 36% in 1995 (Figure 3). This was largely due to increasing population pressure and agricultural activities, and the largest reduction occurred in land, which had slopes of less than 30% (Kammerbauer and Ardon, 1999).

In Papua New Guinea with an average population of less than 10 persons km^{-2}, McAlpine et al. (2001) compared aerial photographs from the early 1970s with Land Sat^{TM} imagery from 1996 and found that there was an increase of approximately 10% in the area of land used for food production. Rural population increased, however, by more than 40%, which indicates that land-use significantly intensified. Ningal et al. (2008) assessed land use change in the Morobe Province (3.4 million ha) using topographic maps and Landsat^{TM} images. Between 1975 and 2000, agricultural land use increased by 58% and population grew by 98%; most new agricultural land was taken from primary forests (Figure 4). The forest area was more than halved from 9.8 ha per person in 1975 to 4.4 ha per person in 2000. Correlation between total population change and total land use change was strongly positive (64%).

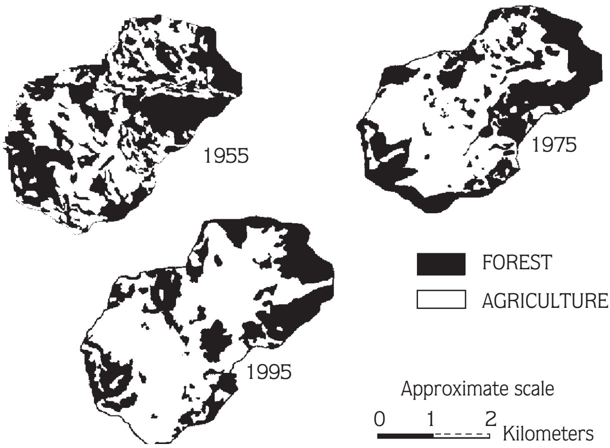

Figure 3. Forest cover maps of the La Lima watershed in the central region of Honduras at different times. From Kammerbauer and Ardon (1999).

China

China mainland territory covers 960 million ha, accounting for 7.2% of the world's land area. Arable land covers about 14% (Li, 2000). China has to feed more than 20% of the global population with less than 10% of the global area under arable land. The average arable land per capita is 0.095 ha (Zhu et al., 2004). This limited arable land is decreasing due to agricultural restructuring, rural industrialization, and rapid urbanization. Furthermore, some 40% of the arable land suffers from soil degradation due to water and wind erosion, salinity etc.

Since the reform in the late 1970s, China has been experiencing significant changes in land use (Table 3, Figure 5). Although China releases statistical data of land use each year, some studies based on remote sensing indicate that the statistical data are biased (Liu and Buheaosier, 2000). From 1980 to 1996, China carried out the detailed land use survey covering the whole mainland except regions of Hong Kong, Macao, and Taiwan. The survey revealed that the area opened up for crop cultivation was 71 million ha, mainly from unused land, pastureland, and forest. About 38.7 million ha of farmland was converted for construction, forest, orchards and water (Li, 2000). Crop land increased by 32.2 million ha between 1949 and 1996. In the same period, the build-up area increased by 19.3 million ha. Most of the new construction land was taken from cultivated land, forest, pasture, and unused land. About 80% of the new land for human settlements and industrial-mining sites converted from cultivated land (Lin and Ho, 2003). Orchards and forest areas increased by 8.9 million ha and 102.6 million ha, respectively, while pastureland decreased by 125.9 million ha (Li, 2000). Most intensive land use changes occurred in the coastal regions of China: the Pearl River Delta, the Yangtze River Delta, and the Bohai Rim (Liu and Buheaosier, 2000).

Area under cereals and yields

The area under rice, wheat, and maize fluctuated between 1961 and 1998. The total area under cereals increased or remained unchanged between 1961 and 1978 during the "Cultural Revolution"; it increased between 1986 and 1990 when the government increased agricultural subsidies. The total area in cereals declined between 1980 and 1985, a period corresponding to the implementation of the land use tenure policy, and

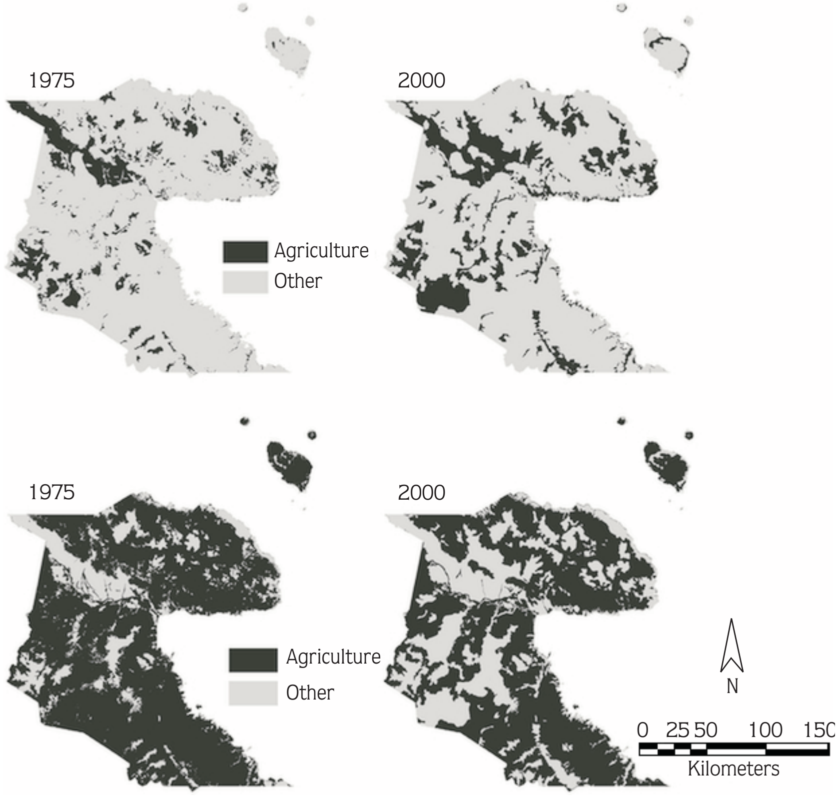

Figure 4. Forest and agricultural land use in 1975 and 2000 in the Morobe province of Papua New Guinea (Ningal et al., 2008).

between 1991 and 1995, when a large proportion of the rural labour force moved to urban areas. The centre of cereal production has moved to the north although the major area planted for rice, wheat, and maize together is still located in southern China.

Yield per hectare for all cereal crops has increased from 1.2 t ha^{-1} in 1961 to 4.8 t ha^{-1} in 1998 although yield per unit inorganic fertilizer use decreased for most crops. The increases in yield per hectare and crop production per capita is mostly due to the rapid increase in inorganic fertilizer use after the land use tenure reform in the late 1970s. With limited reclaimed land resources remaining, increasing food demand will have to come from increased crop yields that may lead to environmental degradation (Tong et al., 2003).

Land Cover Change and Soil Fertility

In the previous section it was shown that land cover is rapidly changing in many parts of the world. The majority of land cover changes are related to agricultural use of the land, including pastures. Agricultural activities change the soil chemical, physical, or biological properties. Such activities include cultivation (mechanised or by hand), tillage, weeding, terracing, subsoiling, deep ploughing, manure, compost and fertiliser applications, liming, draining, irrigation, and impoldering (Bridges and de Bakker, 1997) but also biocides applications on cultivated crops may affect soil properties. Many soils have been improved since people started cultivation and soil improvements continue in many agricultural areas. Inputs are applied when needed by the crops, losses are minimised and environmental awareness and legislation have created agricultural practises that are ecologically and economically more sustainable. All these improvements are usually not reported in scientific literature. We do not have maps showing the great improvements in conditions in the past 100 years – quite the opposite: there is fair a body of literature on soil degradation in relation to agriculture (FAO, 1971; Boels

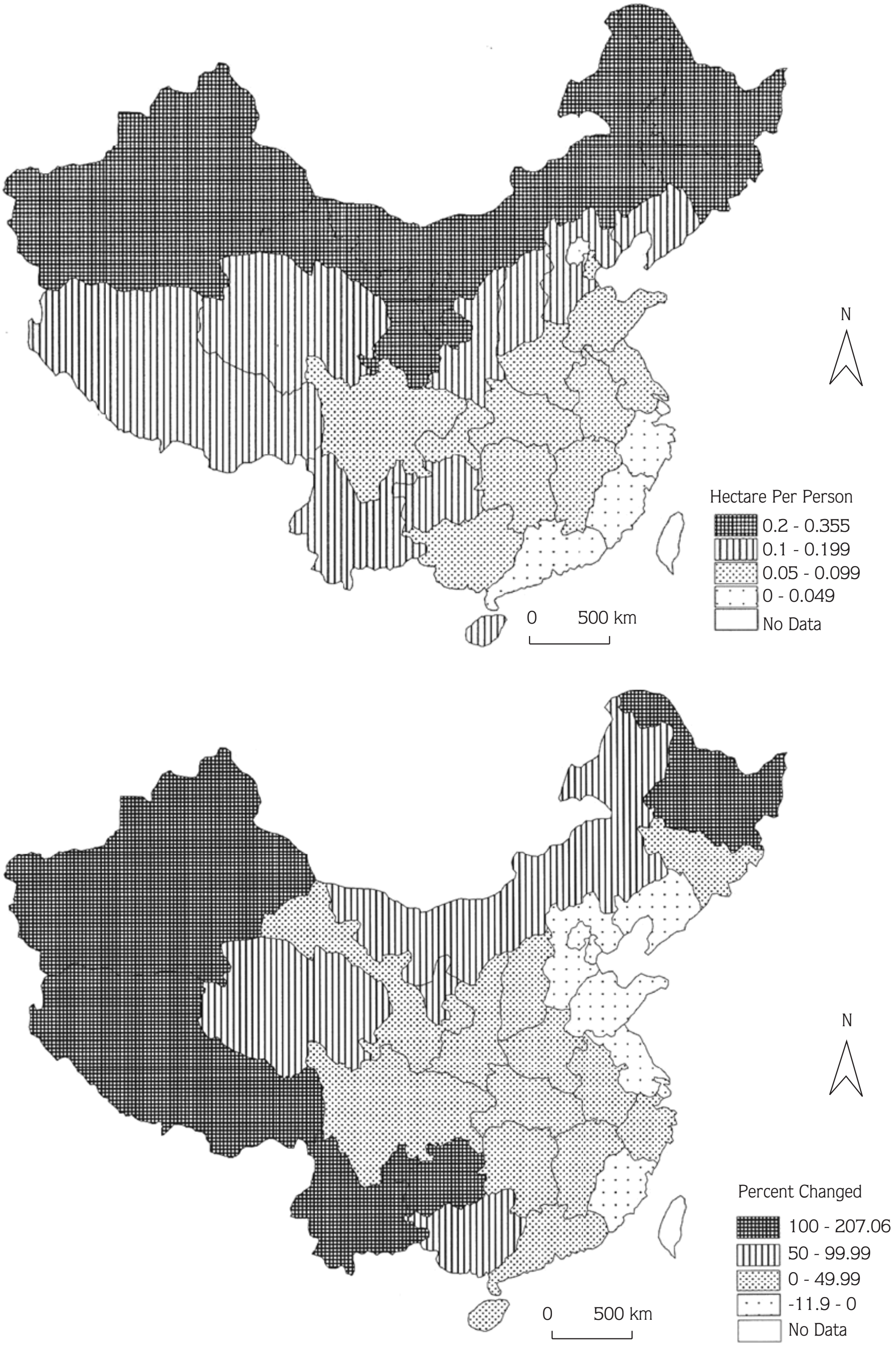

Figure 5. Per capita cultivated land (above) and decline of cultivated land per capita in China (below) between 1949 to 1996 (Li, 2000).

Table 3. Changes in land use in China from 1949 to 1996 (in million ha). Modified from Li (2000).

	1949		1996		Change	
	Million ha	%	Million ha	%	In area million ha	%
Cultivated land	97.8	10.1	130.0	13.7	+32.2	+33
Orchards/plantations	1.1	0.1	10.0	1.1	+8.9	+840
Forest	125.0	13.2	227.6	23.9	+102.7	+82
Pasture	391.9	41.2	266.1	28.0	-125.9	-32
Settlements, industry/mining	4.7	0.5	24.1	2.5	+19.3	+40
Transport	2.0	0.2	5.5	0.6	+3.5	+173
Water area	22.5	2.4	42.3	4.5	+19.8	+88
Unused land	305.5	32.1	245.1	25.8	-60.5	-20
Total area	950.7	100.0	950.7	100.0		

et al., 1981; Dudal, 1982; Lal, 1989; Oldeman et al., 1991; Sanders, 1992; Eden, 1996; Blum, 1997; van Lynden and Oldeman, 1997; Lal, 2001).

Most of the concerns about soil degradation are fully justifiable, but hard data on the severity, extent, and impact are little which makes soil degradation a debated issue – particularly in tropical regions (Hartemink, 2006). A major factor in soil degradation is the soil chemical fertility and then in particular its decline as a result of the lack of nutrient inputs. This has been a major concern since sedentary agriculture started and is the main reason why farmers clear more land when farming in forested areas: the soil is depleted from plant nutrients (FAO-Staff, 1957; Nye and Greenland, 1960). Since the late 1980s, declining soil fertility has been recognised as an important cause for low agricultural production in sub-Saharan Africa (Pieri, 1989; Stoorvogel and Smaling, 1990; van der Pol, 1992; e.g. Henao and Baanante, 1999; Sanchez, 2002).

Here we summarise some of the main studies about soil fertility in each of the land cover change categories. We distinguish 4 major categories: deforestation; the conversion of forest to grassland, cropland (annuals and perennials), and the conversion of pasture to cropland. We added the conversion of wetlands to this list.

Conversion of forest

When reviewing soil changes it is necessary to understand the phases of crop development as they affect collection and interpretation of the data (Hartemink, 2006). When primary forest is replaced by tree crops (e.g. teak or oil palm), the following phases can be recognised - modified from Sanchez et al. (1985) and PORIM (1994):

1. Forest clearing and crop establishment,
2. First years after clearing up to closing of canopy and coming into production,
3. Period of maximum production,
4. Felling and harvesting the first rotation,
5. Beginning of the second rotation.

A large number of studies have focused on soil changes when the forest is cut and crops are planted (phase 1 and 2), and there are excellent summaries available (Nye and Greenland, 1960; Sanchez et al., 1983; Lal, 1986). Information on soil changes between phase 1 and 4 is scarce as it requires long-term research commitment. Under primary forest nutrient cycling may be almost closed and the soil-plant system is often in a steady-state condition. Such a condition is exceptional and there is evidence that even under natural conditions nutrient losses occur (Poels, 1989; Stoorvogel et al., 1997). Deforestation is a drastic land cover change and the clearing and burning of the natural forest has a large impact on soils (Lal, 1986). All deforestation studies find considerable changes in soil physical and chemical properties (Sanchez and Salinas, 1981; Lal, 1986; Ghuman and Lal, 1991; Veldkamp, 1994; Juo and Manu, 1996). Most studies indicate that the abrupt transition from natural climax vegetation to a managed system by man has several short-term effects on soil properties. The most important on-site effect is the loss of organic matter causing a reduction in nutrient stock, CEC, and structure stability. The increase in soil organic C oxidation is due to higher soil surface temperatures in arable soils as compared to soils under forests. Another effect that occurs in deforested sloping areas is erosion (Lal, 1986). This is often mentioned as the main cause for soil degradation (Willet, 1994). Burning of biomass and debris reduces N and S stocks, while deforestation with heavy machinery may cause soil compaction and erosion (Dias and Nortcliff, 1985; Hulugalle, 1994). Compaction effects are particularly severe on volcanic ash soils (Andosols) (Spaans et al., 1989).

A sharp decline in soil organic C and increase in bulk densities in Ultisols was found under various cropping systems up to 4 years after deforestation (Ghuman et al., 1991; Ghuman and Lal, 1991). Conversion from forest to pasture or new forest has smaller dramatic effects on soil organic C and bulk density compared to conversion from forest to cropland. Veldkamp (1994) studied the conversion of forest to pasture on an Andic Humitropept using carbon isotopes (the d^{13}C method) in order to distinguish between soil organic C from forest and grassland. A decline in soil organic C (corrected for compaction) was found followed by a stabilisation after 5 years. The original forest soil organic C continued to decline up to 20 years after deforestation; it was partially compensated for by new produced grass-derived soil organic C.

In the sugar cane areas of São Paulo, Brazil, Caron et al. (1996) sampled an Oxisol and Alfisol under primary forest and 20-years old sugar cane. Topsoil organic C levels were 34 g kg^{-1} in the Alfisol under forest and 16 g C kg^{-1} under sugar cane. In the Oxisols under forest, there was 45 g C kg^{-1} compared to 30 g C kg^{-1} in the soils under sugar cane. The decrease in soil organic C was accompanied by a significant decrease in soil pH in both soil orders, but the drop in pH was larger in Alfisols (Caron et al., 1996).

Cerri and Andreux (1990) measured different C fractions under forest and at a sugar cane plantation in Brazil. The natural abundance of the isotope ^{13}C was used to identify organic C sources in the soil and to determine the changes in soil organic matter when forest is cleared and sugar cane is planted. The approach is based on the difference in the natural ^{13}C abundance that exists between plants having different photosynthetic pathways, mainly C3 (Calvin cycle: forest) and C4 (Hatch-Slake cycle: sugar cane). The ^{13}C/^{12}C ratio of C3 plants is lower compared to C4 plants (Cerri and Andreux, 1990).

Table 4 presents the C content in soils under forest and sugar cane. Total C levels after 50 years of sugar cane cultivation were 46% of the levels under forest. After 12 years of sugar cane cultivation, more than 80% of the soil organic C still originated from the forest but after 50 years the forest C formed 55% of the total C contents in the topsoil. The rate of increase in C originating from sugar cane was slower than the decrease in C that had originated from the forest. The data of Table 4 were used in a regression model for soil organic matter dynamics (Figure 6). The decline in forest derived organic matter continued during the 50 years spanned by the investigation, and the apparent equilibrium value of total soil organic C is based on a balance between gradual build-up of sugar cane derived organic matter and decay of forest based organic matter. For comparison, soil data from pastures showed a larger stable C pool, a more rapid decline of labile forest C but also a much faster accumulation of labile crop C, which returned the total soil organic C levels to that of the forest before deforestation after about 7 years (van Noordwijk et al., 1997).

Some of the differences between the pasture and sugar cane patterns can be explained by the lower annual input of C under sugar cane (0.96 Mg C ha^{-1}) compared to the pasture (7.5 Mg C ha^{-1}) and differences in soil mineralogy and climate (Cerri and Andreux, 1990). Soil texture plays a role and 12 years after conversion from forest to sugar cane, the majority of the C derived from sugar cane is in the coarse sand fraction. About 90% of the C in the clay fraction still has the forest signature after 12 years, whereas after 50 years 70% of the forest derived C persisted in the clay fraction (Vitorello et al., 1989). These data illustrate the importance of clay-organic matter linkages as a C protection mechanism (Hassink, 1992; van Noordwijk et al., 1997).

It matters whether forest is converted to cropland with annual crops (e.g. maize, cassava, or soy beans), perennial crops (e.g. oil palm, cocoa, or rubber), or forest plantations. The conversion of forest to perennial crops usually results in lower levels in the rates soil fertility

Table 4. Carbon content of soils under forest and after 12 and 50 years of sugar cane cultivation (Mg ha^{-1}, 0-0.20 m depth). Modified from Cerri and Andreux (1990).

	Forest	Sugarcane	
		Soils under 12 years of sugar cane	Soils under 50 years of sugar cane
Total C	71.9	44.6	38.5
Stable C originating from the forest	71.9	36.0	21.0
C originating from the sugar cane		8.6	17.3

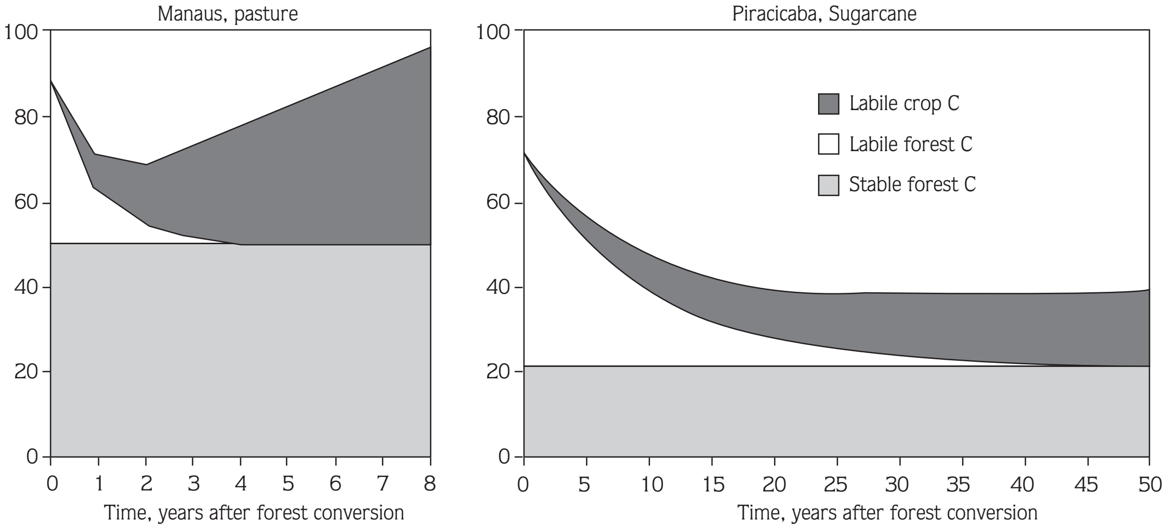

Figure 6. Soil organic matter dynamics in Oxisols after forest conversion to pastures and sugar cane. Graphs based on fitted regression models. From van Noordwijk et al. (1997) based on PhD work by C.C. Cerri in Brazil.

decline because – to some extent - these systems mimic the forest cover (Hartemink, 2005b). Nonetheless, both erosion and soil chemical changes can be significant in the early stages of crop development when the canopy is not closed and the soil not covered. Soil erosion as well as leaching (both leading to a decline in soil fertility) can be high due to the lack of nutrient uptake and soil exposure to the weather.

Conversion of grasslands

There appears fewer studies on the effects of grassland to cropland conversion than on the forest to cropland conversions which has been studied in much more detail. Many soils in Australia, Europe and the US under cereal crops were grasslands before they were cultivated. Conversion of these grassland has caused a decline in soil organic C. This decline reduced the nutrient stocks and resulted in the off-site effect of increased water and wind erosion. Especially in the USA, the large scale conversion of grassland in the central plains to cropland caused severe soil erosion (Bennett, 1939).

Pennock et al. (1994) studied soil property changes after the conversion of grassland to cereal cultivation on Mollisols and Inceptisols in depressions of an undulating till plain of Canada. The inventory was conducted for different landscape elements and illustrate the role of landscape processes in shaping soil properties (Pennock and Veldkamp, 2006). Soil redistribution rates are described within the landscape by radionuclide ^{137}Cs measurements. The relative contribution of on-site mineralisation and off-site soil redistribution to soil organic C changes within the landscape were calculated for 3 landscape positions: shoulder complex, footslope complex, and depressions. In addition, they had areas with the original prairie vegetation and areas used 12, 22, and 80 years for grain production. Changes in SOC were different for each landscape position but the relative contributions of mineralisation and soil redistribution changed with the position in the landscape and in time. The shoulder complex has a strong temporal SOC decrease with an increasing importance of erosion in time. The footslope complex shows lesser SOC degradation. Here the SOC change is more dominated by on-site mineralisation. In the wet depressions there was a SOC increase due to the combined effects of sedimentation and mineralisation. This is one of the few studies that looked at soil changes when grassland was converted to cereal cropland.

Hartemink (1998) sampled selected soils and collected archival soil data at a sugar cane plantation in Papua New Guinea. Soils were sampled under natural grassland prior to the establishment of the plantation (1979) and thereafter under sugar cane. Soil chemical properties between 1979 and 1996 and the topsoil pH decreased from about 6.5 under natural grassland to 5.8 after 17 years of sugar cane cultivation (Table 5). The soil acidification was accompanied by a decrease in exchangeable bases and CEC. Fluvisol and Vertisol topsoils under natural grassland had average organic C contents exceeding 51 g kg^{-1} in 1979 whereas in 1994 and 1996 organic C contents were below 36 g kg^{-1}. Levels of available phosphorus also decreased when grassland was converted to sugar cane, but variation in the data was large.

Conversion of coastal wetlands

In coastal wetlands with tidal swamps and inland marshes containing sediments with pyrite, acid sulphate soils may develop due to oxidation when these sediments are drained or excavated. Especially mangrove conversion to arable lands is a major cause for the development of acid sulphate soils in Africa and SE Asia (Dent and Pons, 1995). The formed sulphuric acid reduces the soil pH below 4, sometimes even below 3. Under these acid conditions clay minerals liberate soluble aluminium that kills vegetation and aquatic life or stunts growth and breaks down resistance to diseases. The most pronounced off-site effect is acid drainage water, which will affect ground and surface water quality. The hazards presented by acid sulphate soils are predominantly in coastal wetlands where land hunger and development pressure are large. It is estimated that globally a total of about 24 million ha land contains acid sulphate or potential acid sulphate soils – many of them in tropical regions.

China

Impact of land cover change on soil fertility varies between the regions. In the hill region of subtropical China (Jiang Xi) it was found that soil properties showed large variability, particularly available P (Sun et al., 2003). Between 1985 and 1997, a significant decrease in soil organic C appeared with original land use patterns of wasteland and paddy field. Other properties showed no significant changes. Fertilizer use in the uplands increased available P and K, whereas it was decrease in forest restorations. When wasteland was changed to paddy soil fertility increased. Soil properties decreased in the southeast of the research area where the land use was paddy whereas soil fertility increased in areas where wasteland was transformed into cropland (Sun et al., 2003).

Soil nutrients declined by 10% as a result of changing land use between 1980 to 1994 in Nanning, Guang Xi Zhuang Autonomic province, in the red soil region. The decrease was largest for available K (-14%). Most soil nutrient levels of cultivated land in the uplands decreased, but the decreases in soil fertility in forest and fruits garden land were absent (Qing, 1999).

A case study in Zunhua County, northern China from 1980 to 1999 indicated that the areas of farmland, grassland, and paddy decreased and were replaced by forest and residential land. Soils under forest in 1999 transformed from farmland in 1980 increased in organic matter by 21%, total N by 18%, available N by 65%, available P by 17% and available K by 17%. Similarly, in the area which was converted from farmland in 1980 to grassland in 1999, soil organic matter, total N, available N, available P, and available K all increased. Changes from farmland to forest and grassland not only changed land cover but also improved soil fertility (Fu et al., 2001).

The Loess Plateau has dramatic changes in land cover over past decades. The natural vegetation has been destroyed, and the landscape is dominated by cropland with some shrub land, grassland, woodland and orchard.

Table 5. Topsoil (0-0.15m) chemical properties of Fluvents and Vertisols between 1979 and 1996. The soils were under grassland in 1979 and thereafter under permanent sugar cane. Values are the arithmetic mean ±1 SD. Modified from Hartemink (1998)

Soil order	Year	Number of samples	pH H_2O (1:2.5)	Organic C (g kg^{-1})	Available P (mg kg^{-1})	CEC (mmolc kg^{-1})	Exchangeable cations (mmolc kg^{-1}) Ca	Mg	K
Fluvents	1979†	15	6.5 ± 0.4	58 ± 15	nd	389 ± 43	228 ± 78	93 ± 41	13.0 ± 5.0
	1982	14	6.2 ± 0.1	nd	36 ± 4	459 ± 55	275 ± 35	113 ± 24	12.9 ± 2.0
	1983	44	6.3 ± 0.1	nd	37 ± 10	435 ± 48	256 ± 35	100 ± 16	12.4 ± 2.8
	1994	12	5.9 ± 0.1	35 ± 6	28 ± 9	384 ± 65	232 ± 47	101 ± 22	10.8 ± 2.3
	1996	8	5.8 ± 0.2	31 ± 7	28 ± 12	374 ± 33	220 ± 30	99 ± 13	8.0 ± 2.0
Vertisols	1979†	6	6.6 ± 0.1	52 ± 9	nd	421 ± 21	293 ± 69	123 ± 39	15.5 ± 2.7
	1982	17	6.2 ± 0.1	nd	43 ± 5	490 ± 29	286 ± 22	131 ± 16	16.1 ± 2.9
	1983	40	6.3 ± 0.2	nd	40 ± 13	477 ± 94	290 ± 83	114 ± 33	12.9 ± 2.3
	1994	12	5.9 ± 0.1	32 ± 3	32 ± 11	452 ± 79	273 ± 50	129 ± 34	13.4 ± 3.9
	1996	12	5.8 ± 0.2	32 ± 6	28 ± 11	421 ± 102	276 ± 73	115 ± 38	9.0 ± 3.0

† Soil samples taken in natural grassland prior to the establishment of the plantation.
nd = no data

In the Danangou catchment, soil organic matter and total N in woodland, shrub land, and grassland were significantly higher compared to fallow land and cropland. Higher levels in soil fertility were found in crop-fruit intercropping. Soil nutrient distribution and responses to landscape positions were variable depending on slope and the location of land use types (Wang et al., 2003).

There are extensive alpine grasslands in Northern China. Studies on the impacts of land use on soil erosion and soil fertility in alpine grassland revealed that the cultivation of grassland increased soil erosion, and after more than 40 yr of cultivation soil organic C had decreased by 55%. Regionally, 59% of the soil organic C was lost within 30 to 50 years of cultivation. There were concomitant losses of total N and cation exchange capacity. On cultivated soils, both soil erosion and mineralization caused the organic C losses. Pasture degradation and cultivation also caused changes in soil P. This study showed that grassland degradation and cultivation caused not only severe soil erosion, but also soil fertility decline (Wu and Tiessen, 2002).

In the middle reaches of the Heihe River basin, the largest inland basin in the arid northwest China, land use change from cultivated land to desert grassland indicted that after the first 3 to 5 years of cultivation soil N and P contents of former grassland soils decreased significantly. After 13 years of cultivation, soil nutrient content in former mountain grasslands gradually stabilized, whereas soil fertility increased in desertified grasslands where cultivation had been abandoned. It was estimated that the transformation of grassland into cultivated land and that of cultivated land into desert grassland resulted in organic C emissions of 1.68 Tg C and 0.55 Tg C, respectively, over the 13-year period. Land use changes in the arid inland region significantly influenced soil organic C pools and cycles (Wang et al., 2004).

Discussion

In this paper we reviewed some of the major studies on global land cover change. Significant changes are found but the spatial data is unevenly distributed and many uncertainties remain. Given the importance of land cover change and its effect on major earth system processes the rapid advances in remote sensing will allow for a reduction in the uncertainties and timely understanding of drivers, processes and factors in land cover change. A major challenge for remote sensing is the translation of cover characteristics to relevant soil and land use information.

The case studies showed major changes in land cover that could be quantified since the 1930s (North Lampung), 1950s (Honduras, Kenya), or 1970s (Burkina Faso, South Sumatra, Tanzania, Papua New Guinea). Changes in land cover reflect the rapid population growth, which occurred almost universal in the areas under study although the relation between agricultural expansion and population growth is unlikely to be linear (Meertens et al., 1996) and several factors interact in this complex process (Lambin et al., 2003). In most countries, the area under natural forest declined when the population increased. A national survey in Kenya revealed, however, an increase in planted tree biomass in many smallholder agricultural systems (Holmgren et al., 1994) and this was confirmed in large scale surveys (Tiffen et al., 1994; Imbernon, 1999b). This tendency of land use intensification is interpreted to be a response to increasing lands scarcity. On the other hand in Malawi and in parts of Tanzania no increase in planted tree biomass was observed (Kaoneka and Solberg, 1997; Abbot and Homewood, 1999). Part of the biomass increase in the Embu Region (Kenya) was caused by the increase in perennial tree crops in smallholder farming systems which was also observed in Sumatra where plantation agriculture increased at the expense of rain forest.

The case studies showed that land cover changes occur and the quantification of agricultural land has been facilitated by aerial photographs and satellite images (Seto et al., 2000; Jansen and Di Gregorio, 2002). Studying change in land cover is not a goal in itself and they could be used for land-use planning or to analyse spatial patterns of soil fertility changes, or regional nutrient budgets (Hartemink, 2005a). However, the scale at which the observations are made may not be directly applicable to the scale at which the factors that drive land-use change can be predicted or influenced. From the studies reviewed here there is no overwhelming evidence that land-use changes lead to massive environmental degradation although it can be anticipated that land use intensification without external inputs or the encroachment of marginal areas may lead to soil degradation. However, it should be stressed that not all changes are negative as many forms of land use change increase food and fibre production, resource use efficiency, and human health and well-being (Lambin et al., 2003).

The effects of land cover changes as well as subtle conversions on soil fertility are fairly well-documented (Murty et al., 2002). Land use change always affects soil quality and productivity. On-site effects are mostly related to changes in soil organic matter content. The most dramatic changes occur directly after a major land use conversion, such as deforestation. Mineralisation increases while the change in cover usually induces erosion and other landscape processes. Conversion has a large short term (1-5 years) on-site impact on soil properties such as soil organic C and bulk density, whereas land use intensification has longer term (10 to 80 years) effects on soil properties. We reviewed some studies in which the trends and rates of soil fertility changes were varying. Obviously, soil fertility is a complex issue consisting of several attributes that interact over time. Measurements require long-term research commitment as well as detailed knowledge about spatial and temporal variability (Hartemink, 2006). Most studies about the interaction between land use and soil fertility are on the profile and field scales which makes a direct link with spatial data on land cover change complicated. Systematic, consistent measurements of soil properties should be undertaken at a global scale, at a relatively fine resolution, since soil attributes are an important component of land cover (Lepers et al., 2005).

The ability of a region of the world to produce or access food is determined by access to an adequate amount of productive cropland, the ability to maintain high crop yields on that land (often with the aid of external inputs, such as fertilizers, pesticides, and irrigation), or the ability to purchase and import food from other regions (Ramankutty et al., 2002b). The majority of the world's fertile soils are already under cultivation (Young, 1999). Much of the remaining cultivable land lies in marginal areas or in the richly forested regions of tropical Latin America and Africa. Clearing for cultivation implies a loss of forest. Prime farmland is lost to urbanization and the impact of soil degradation will further increase the pressure on the remaining croplands. Our global food production system is dependent on technological improvements to meet future food demands (Ramankutty et al., 2002b) but in the absence of new areas that can be opened for cultivation without the loss of forest cover only increases in crop yield (unit per area) can feed the bourgeoning human population.

Agricultural ecosystems have become incredibly good at producing food, but these increased yields have environmental costs that cannot be ignored (Tilman, 1999; Tilman et al., 2002). Increased precision in the application of external inputs at a time that the crop can utilise these inputs allows for reduced environmental impact. Alternatively, one can explore the different landscape properties and connectivities by including a landscape perspective in farming, leading to the closure of local and regional nutrient cycles (e.g. Veldkamp et al., 2001).

Farming operations are built around rapid advances in GPS, GIS, and agrotechnologies and precision agriculture is becoming increasingly important in several countries in temperate regions (Viscarra Rossel and McBratney, 1998; Bouma et al., 1999; Sylvester-Bradley et al., 1999) but also has potential for farming in tropical countries (van Groenigen et al., 2000; Dobermann et al., 2003; Yemefack et al., 2005). Linking advanced management technologies to spatial land cover data warrants further research.

Conclusions

Globally, land use has changed considerably in the past decades – mostly reflecting the enormous growth in human population and their need for food. The world's population has doubled since 1960. The developing world accounts for about 95% of the population growth with Africa as the world's fastest growing region. The growing population has many implications but most of all it requires an increase in agricultural production to meet food demand. This demand can be met by expansion of agricultural land or by intensification of existing systems. Conservation and improvement of the natural resources on which agricultural production depends is essential. Soil degradation, and in particular the decline of soil chemical fertility, is a major concern in relation to food production and the sustainable management of land resources. It also affects land use but the spatial and temporal effects of soil fertility change and its interaction with land cover change remains to be investigated. Many studies on soil land use and land cover change are local and mainly aimed at specific systems such as shifting cultivation. Emphasis should be put on intensive land use systems at more aggregated scales and in a spatially explicit way.

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