**Supporting Online Information**

***A conceptual framework for analysing and measuring land-use intensity***

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# Research themes in studies of land-use intensity

Research on land-use intensity reaches back to the mid-19th century when the British economist T.R. Malthus (1766 – 1834) explicitly addressed agricultural intensification in the context of population growth. The economic perspective on land-use intensity is rooted in the work of D. Ricardo (1772 – 1823, e.g. the law of rent (Ricardo, 1817) and of J.H. von Thuenen (1783 – 1850) who empirically studied and conceptualized input-output relations of land-based production, and developed an own land rent-theory (von von Thuenen, 1826). Research on the nexus between land-use intensification and population growth re-gained impetus after the Second World War with the rediscovery of the work by Chayanov (1888-1937) and by Ester Boserup (1910 – 1999) and became a central theme of land-use intensity research in such disciplines as human geography, ecological anthropology or political ecology addresses an understanding of agricultural change and its drivers. Around the early 1990ies, land-use intensity became somewhat neglected in land-use research, while it still played a substantial role in anthropological studies. The availability of high-resolution land-cover data brought the study of land-cover change into focus of land-use research, but also diverted attention from intensification processes (Erb, 2012), because most the changes associated with intensification are not related to changes in land cover and thus not detectable by remote sensing (Erb et al., 2007; Verburg et al., 2011). In recent years, however, intensification moved again to the centre of interest of a broader scientific community, due to its far-reaching, potentially detrimental ecological consequences, emerging new demands for land products and the systemic interrelation between intensification and land expansion (the so-called land-sparing vs. land-sharing debate.

In the following, we will sketch the main lines of thoughts and insights of these four research clusters: the economic perspective, the population-intensification discourse, the environmental consequences of land use intensification, and the land-sparing-land-sharing debate.

## Economic perspectives on land-use intensity

Agricultural economists have a long tradition of studying agricultural intensification at the farm level, and much of this research is rooted in the land rent theory by von Thünen and the law of diminishing returns by Ricardo. Ricardo conceptualised the interrelation between one input factor (labour or capital) and the output (produce) from land use to characterise the decrease in the marginal output at an increasing level of production input (Ricardo, 1815). Von Thünen established relationships between market distance, agricultural production and land use. Whereas transport costs increase with distance to markets, locational rents (and land values) decrease. Certain land uses are thus restricted to “rings” of profitability and competitiveness, and thus also land-use intensity, the so-called “von Thünen rings” (von Thuenen, 1826; Nelson, 2002). Another seminal principle of von Thünen holds that agricultural intensification is only economically rational when the increases in the input costs are smaller than the additional profits from the increased production. With these contributions, Ricardo and von Thünen are regarded as the founders of political and agricultural economy, economic geography and the “rational-choice” notion in land-use decisions, which is followed in many land-use models (see Heistermann et al., 2006).

In economic terms, land-use intensity refers to the quantity of production inputs (capital[[1]](#footnote-1) or labour) per unit of land. The intensification of production, thus, denotes a higher use of one or more production inputs per unit of land, sometimes even at the expense of decreasing efficiency, due to diminishing returns. The inputs may be substitutive (e.g., machinery may replace labour) or complementary (e.g., more fertilisers may require increased pesticide use). The biophysical process that transforms inputs into outputs is captured with production functions, and technical change is assumed to modify these production functions, allowing for productivity increases. The input-output relations below the production function imply technical inefficiencies in the use of production factors, whereas economically suboptimal points on the production function imply allocative inefficiencies (Farrell, 1957). Economists mostly study land-use intensity from a rational choice (utility optimisation) perspective in which the producers are assumed to choose an optimal combination of inputs and outputs. Changes in price signals for inputs and outputs or changing technologies will alter the optimal production programme and may result in land-use intensification. The monetary objectives of individual agents are in the centre of attention, whereas the environmental effects of production are treated as externalities (Hanley et al., 2007). Internalising negative externalities results in increased production costs, which may reduce the incentives for land-use intensification and, thus, reduce the overall output (Pender, 1998).

## Research into intensification, population and technological innovation

With the “Essay on the Principle of Population”, Malthus (1798) hypothesised that an exponential population increase is inevitably limited by linearly increasing yields and, hence, will lead to famine and wars. Thus, technological change in agriculture would exert an endogenous population control. More than 150 years later, Ester Boserup challenged this reasoning by asserting that the primary goal of cultivation is to provide an ample supply of food while maximising labour productivity. Hence, the incentive for agricultural intensification will only arise with population growth because the adoption of technologies increases production at the expense of labour productivity. This insight is shared with the Russian agronomist Chayanov (1986; see Turner and Ali, 1996) and the American anthropologist Netting (Netting, 1993).

Geertz (1963) described production increases without technological innovation but with significant declines in the marginal utility of the sum of inputs, a process coined “agricultural involution”. This phenomenon led scholars to discern “innovative intensification” (i.e., the adoption of new technologies that allow for higher output per unit of input) and “non-innovative intensification” (i.e., the decline of production despite increases of inputs in the absence of new technologies) (Laney, 2002; Keys and McConnell, 2005). A central aspect of Boserup’s notion is the observation that increasing land-use intensity allows the enhancement of land productivity to match population growth and results in alterations of ecosystem properties, which promotes technological innovation. The essence of intensification is its role to maintain fertility and, therefore, to prevent degradation in agriculture (Boserup, 1965). Other authors interpret the occurrence of land-use-induced ecosystem degradation as evidence for deficiencies in Boserup’s optimistic view on intensification (Blaikie and Brookfield 1987). The key to Boserupian intensification is, according to Stone (2003), that higher labour inputs are both necessary (more production requires more work) and sufficient to increase production (increasing work succeeds in increasing output).

The insights provided by Boserup and Chayanov inspired many researchers to analyse the interrelation of population pressure, technological change and land-use intensification (Brown and Podolefsky, 1976; Turner et al., 1977; Netting, 1993; Krautkraemer, 1994; Angelsen, 1999). The simplified Boserupian notion of population as the principal driver of intensification (‘induced intensification’; Turner and Ali, 1996) was challenged by authors who emphasise a number of economic, social or political factors as being decisive for land-use intensification (Grigg, 1979; Blaikie and Brookfield, 1987; Turner and Brush, 1987; Hunt, 2000; Brookfield, 2001; Stone, 2003).

## Research on the ecological consequences of intensification

Another important research strand on land-use intensity that gained impetus, particularly in the 1990s, can be found in the research literature focussing on the ecological consequences of land-use intensification. Landmark studies in this field are the seminal reviews by Matson et al. (1997), Gregory et al. (2002), and Stoate et al. (2001, 2009), summarising the ecological consequences of the intensification of arable and grassland systems, including the specialisation of production (monocultures), higher pest prevalence, impacts on soil biota and soil carbon, and the increased availability of nutrients and toxins (e.g., pesticides) in land systems. Similarly, Steinfeld et al. (2006) summarised the manifold effects of livestock intensification (e.g., increasing stocking rates, higher input-output efficiency), suggesting that livestock systems are major contributors to the urgent global environmental challenges, such as climate change, altered nutrient cycles, water pollution, and soil degradation (McDowell, 2009; Pelletier and Tyedmers, 2010). Forestry intensification in boreal conditions e.g. in Sweden, such as the introduction of fast growing tree varieties and fertilization, has also been associated with risks of adverse environmental effects on soil resources and water quality (Laudon et al., 2011).

The relationship between land-use intensity and biodiversity is a particularly prominent focus of this branch of research. The negative influence of increasing land-use intensity on the biodiversity of farmland is well documented (Donald et al., 2001; Kremen et al., 2002; Hendrickx et al., 2007; Firbank et al., 2008, 2008; Kleijn et al., 2009; Fischer et al., 2010; Le Féon et al., 2010). Within a broader context, this research strand focuses on the impact of land use on the provisioning of essential but non-marketed ecosystem services (Tilman, 1999; Kremen, 2005; Millennium Ecosystem Assessment, 2005; Tscharntke et al., 2005; Foley et al., 2011; Kumar et al., 2013).

## The land sparing vs. land sharing debate

The hypothesis that increased agricultural yields lead to reduced land demand, first formulated by Borlaug (2007), is central to a recent debate on land-use intensification (Balmford et al., 2005; Fischer et al., 2008; Phalan et al., 2011): agricultural productivity per unit area would translate into a reduced land demand if it would spare these lands for other uses (Waggoner and Ausubel, 2001) and may, thus, benefit forest protection, carbon sequestration and biodiversity conservation. It has been suggested that the intensification of the livestock sector (Steinfeld et al., 2006) and the closure of yield gaps (Foley et al., 2011) may provide great potential for land sparing. Several empirical studies are providing evidence for such land-sparing effects of intensive land use (e.g., Green et al., 2005; Burney et al., 2010; Phalan et al., 2011). In forestry, intensive forest plantations have also been advocated because of their potential to release pressures on natural forests (Bowyer, 2001; Brockerhoff et al., 2008).

Another school of thought challenges this view, arguing that intensification may not necessarily lead to land being spared for other purposes, for example, because of the displacement of production abroad or due to rebound effects that translate efficiency gains into increased absolute production (Fischer et al., 2011; Lambin and Meyfroidt, 2011; Erb, 2012). Interestingly, Rudel et al. (2009), for example, do not find conclusive empirical evidence for the existence of the land-sparing effect of intensification over the past five decades. There is also substantial concern about the externalities in the current land-sparing assessments, which typically focus on a single biodiversity indicator, in that the land-sparing position discounts that many species may depend on low-intensity agriculture and that many areas may not be suitable for intensification due to environmental or institutional reasons. Proponents of the land-sharing view typically argue for a strategy favouring agro-ecological systems that are less intensive in terms of capital inputs but highly intensive in terms of labour and land and that adopt wildlife-friendly farming techniques (Fischer et al., 2008, 2011; Ranganathan et al., 2008; Clough et al., 2011).

Table 1. A selection of definitions and metrics related to land-use intensification

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| **Author** | **Definition** | **Proposed metric** |
| **Inputs** |  |  |
| Boserup, 1965. p. 34 | […] define the concept of intensification […], namely as the gradual change towards patterns of land use which make it possible to crop a given area of land more frequently than before. | Cropping frequency, proportion of fallow land |
| Brookfield 1972, p. 31 | “in regard to land, or to any natural resource complex, intensification must be measured by inputs of capital, labour and skills against constant land. The primary purpose of intensification is the substitution of these inputs for land, so as to gain more production from a given area, use it more frequently, and hence make possible a greater concentration of production” | Inputs of labour and capital (and skills) against constant land |
| Brookfield and Hart, 1971, p. 89-90 | Inputs relevant - Production is not significant to the measurement of intensity | Inputs decisive, outputs not important |
| Brown and Podolefsky, 1976 | Base a rank order scale for agricultural intensity on skills related to technology, as suggested in Brookfield (1972, p. 32) | Technology input |
| Turner et al., 1977 | “We use the proportion of time that each crop-fallow cycle is in the cropping phase as the degree of agricultural intensity” | Cropping frequency |
| Dayal, 1978, p. 289 | “A precise measure of agricultural intensity is the ratio of the quantity of inputs to constant land.” | Inputs |
| Turner II & Brush, 1987, p.17 | *“Intensification* is often used to describe technological change involving greater use of labour or other inputs per unit of land” | Inputs of capital; labour per area |
| Turner and Doolittle, 1978, p297 | “To intensify agriculture usually involves an increase in the frequency of cultivation (Boserup) and an increase in technique-skills (Brookfield).” | Cropping frequency; technology |
| Netting, 1993, p. 262 | “Intensive agriculture is a term that specifies a higher total output in the spatial and temporal extent than could be produced by extensive means, and it applies particularly to land use that maintains an area in crop production for more years than it is fallowed” | Output per area |
| Stone, 1994, p. 317  | “Intensification is the substitution of labour for land. Intensification increases […] agricultural output per unit of area and unit of time but only by exacting higher marginal costs in labour and capital” | Inputs of labour and capital, with reference to outputs |
| Giller et al., 1997, p.4 | “Agricultural intensification is a set of patterns of land-use change with the common feature of increased use of the same resources for agricultural production, usually as a result of a switch from intermittent to continuous cultivation of the same area of land.” | Inputs; cropping frequency |
| Kleijn et al., 2009, p. 904 | […] land-use intensity is used in the latter, more general sense, because management (e.g. N input level, pesticide application rate, cutting frequency) is more likely to be related to biodiversity than yield per se. | N-inputs, pesticides application, cutting frequency |
| Temme and Verburg, 2010, p. 47 | Nitrogen inputs | Inputs |
| Siebert et al., 2010 | Cropping intensity | Cropping frequency |
| Noble and Dirzo, 1997, p. 523 | “There is a continuum of management approaches, ranging from no preparation of the site for regeneration after logging, through raking and burning of slash, to more intensive preparation of the soil surface for seed from either natural or artificial sources.” | Rotation frequency, preparation of regeneration |
| Teillard et al., 2012, p. 136 | “ […] defined as the ratio between the sum of different categories of input costs and the total Utilized Agricultural Area (UAA) of the farm | Inputs costs |
| Powers, 1999, p. 277 | “Rotations are shortened to capture a good return on the costs of investment.” | Rotation frequency |
| **Outputs** |  |  |
| Turner II & Brush, 1987, p. 6 | “Output intensity refers to yield or production per unit area and time” | Output per area and time |
| Netting, 1993. p. 271 | *“Intensification* […] refers to the productivity of land that can be raised by technology and by labour, of various kinds and in different proportions” | Productivity of land |
| Turner & Doolittle, 1978, p. 298 | “Our ideal measure of agricultural intensity is: food-tons or number of calories/hectare/20 years” - (input data can be surrogate measures of intensity) | Output per area and time  |
| Shriar, 2000p. 305 | output per unit area is likely to be the ideal measure of intensity because it makes no presumptions about the effect of inputs on productivity (Netting, 1993: 262) and because, after all, production is the principal objective of agricultural activity.” | Output per area |
| Gregory et al., 2002, p. 280 | “producing more of the desired products per unit area of land already used for agriculture” | Output per area |
| MacLeod and Moller, 2006, p.203 | “Grazing intensity was quantified using stocking density estimates for the sheep, deer, beef and dairy sectors” | Stocking density |
| Berka et al., 2001, p. 394 | “A … indicator of intensification is the increase in animal densities” | Stocking density |
| Burney et al., 2010, p 12052 | “[…] by improving crop yield from the land already under cultivation (intensification).” | Crop yield |
| Smith et al., 2010, p. 2945 | “Producing more of the desired products per unit area of land already used for agriculture or forestry.” | Output |
| Dietrich et al., 2012, p. 110 | “Degree of yield amplification caused by human activities” | Crop yield |
| **Increased outputs through increased inputs** |  |  |
| Cassman, 1999 | “The most salient feature of these intensified systems was greater yield per unit land and time. […] three production factors were largely responsible for the increased production […] (i) new ‘‘miracle’’ varieties which had a higher harvest index (HI; the ratio of grain to total crop biomass), […] ii) increased application of N fertilizer, iii) […] irrigation […],” | Yields vs. harvest index, fertilizer, irrigation |
| Herzog et al., 2006, p.166 | “Increasing the intensity of agricultural production in terms of increased yields per area of land and per unit of input (labour and capital) […] “ | Yields vs. labour and capital  |
| Tilman et al., 2011, p. 20261 | “[… ] achieving higher yields through increased inputs, improved agronomic practices, improved crop varieties, and other innovations” | Yields vs. breeding, fertilizer, irrigation |
| Le Féon et al., 2010, p143 | “Intensive agriculture is characterized by high productivity, high input of pesticides and fertilizers, low proportion of permanent grasslands in the landscape” | Yields vs. pesticides, fertilizers, land use mix |
| Smith, 2013, p. 18f | “… the process of delivering more safe, nutritious food (e.g. tonnes of cereal, tonnes of meat, litres of milk, kilocalorie of food energy, gram protein, nutrients etc.) per unit of input resource (e.g. land area, energy input, fertiliser input, other agrochemical input etc.)” | Yield vs. land, energy, fertilizer, agrochemical inpouts |
| **Altered system properties** |  |  |
| Matson et al., 1997, p. 504 | “One key feature of agricultural intensification has been increasing specialization in the production process, resulting in reduction in the number of crop or livestock species, or both, that are maintained, often leading to monoculture” | Changes in biodiversity |
| Keys and McConnell, 2005, p. 321 | “Agricultural intensification […] involves the alteration of plants and animals from dependence on states and flows not managed by people to those managed by people.” | Changes in dependency from human management  |
| Tscharntke et al., 2005, p. 858 | “The dramatic landuse changes include the conversion of complex natural ecosystems to simplified managed ecosystems […]” | Proportion of simplified, managed ecosystems |
| Haberl et al., 2007, p. 12943 | “ […] humans alter ecological energy flows, [an indicator for] the intensity of human domination of ecosystems.” | Changes in net primary production |
| Stevens et al., 2010, p. 2943 | “Management intensity (estimated from standing crop biomass)” | Changes in standing crop biomass |
| Kirch et al., 2012, p. 23 | “Agricultural intensity was determined by measuring the density of agricultural alignments in each cell of a 0.25 ha grid superimposed over the undisturbed area” | Density of alignments |
| Luyssaert et al., 2011, p. 3273 | “ […] to calculate the difference between potential and actual biomass storage” | Change in biomass storage |
| Schall and Ammer, 2013, p.11 | The approach to quantify SMI [Silvicultural management intensity] presented in this study combines three main stand characteristics of a given stand: tree species, age and biomass. These factors are represented by ifferent risks, which are a function of tree species and age, and different stand densities, which are a function of the silvicultural regime and stand age”  | Combination of species, age and biomass  |

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1. The capital goods, such as pesticides, fertilisers, manure, feed, seed, and fuel, are sometimes listed under “intermediate inputs”, see Cornia (1985). For the sake of brevity, we adhere to the classical notion of capital as the production factor that subsumes intermediate inputs. [↑](#footnote-ref-1)