nature sustainability
SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41893-018-0070-8
In the format provided by the authors and unedited.

Social-ecological outcomes of agricultural intensification

Laura Vang Rasmussen[1,2], Brendan Coolsaet[3,4], Adrian Martin[3*], Ole Mertz[1], Unai Pascual[5,6], Esteve Corbera[7], Neil Dawson[3], Janet A. Fisher[8], Phil Franks[9] and Casey M. Ryan[8]

[1]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark. [2]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada. [3]School of International Development, University of East Anglia, Norwich, UK. [4]European School of Political and Social Sciences, Lille Catholic University, Lille, France. [5]BC3, University of the Basque Country, Leioa, Spain. [6]Ikerbasque, Basque Foundation for Science, Bilbao, Spain. [7]Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Barcelona, Spain. [8]School of Geosciences, University of Edinburgh, Edinburgh, UK. [9]IIED, London, UK. *e-mail: Adrian.Martin@uea.ac.uk

Social-ecological outcomes of agricultural intensification

Laura Vang Rasmussen[1,2], Brendan Coolsaet[3,4], Adrian Martin[3*], Ole Mertz[1], Unai Pascual[5,6], Esteve Corbera[7], Neil Dawson[3], Janet Fisher[8], Phil Franks[9], Casey M Ryan[8]

[1] Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark
[2] Department of Forest & Conservation Sciences, University of British Columbia, Vancouver, Canada
[3] School of International Development, University of East Anglia, Norwich, UK
[4] European School of Political and Social Sciences, Lille Catholic University, France
[5] Basque Centre for Climate Change (BC3), University of the Basque Country Scientific Park UPV/EHU, 48940 Leioa, Bizkaia, Spain
[6] Ikerbasque, Basque Foundation for Science, Marıa Dıaz de Haro 3, 48013, Bilbao, Bizkaia, Spain
[7] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Barcelona, Spain
[8] School of Geosciences, University of Edinburgh, Edinburgh, UK
[9] International Institute for Environment and Development (IIED), London, UK
[*]Corresponding author

SUPPLEMENTARY NOTES

Definition of terms used

Ecosystem Services

We followed the Millennium Ecosystem Assessment[1] breakdown of ecosystem service categories: food; freshwater; fuelwood; fiber; biochemicals; genetic resources; climate regulation; disease regulation; water regulation; water purification; pollination; spiritual and religious benefits; recreation and ecotourism; aesthetic, inspirational or educational benefits; sense of place; cultural heritage; soil formation; nutrient cycling; primary production. Because of the increasing scientific interest in the close link between biodiversity and the provision of ecosystem services[2], we also extracted information on changes in biodiversity following agricultural intensification.

Land use intensification in agrarian landscapes

The term intensification in agrarian landscapes is used throughout as referring to the movement from an extensive to an intensive production system or from a subsistence production system to a commercial one[3]. Broadly speaking, the purpose is to increase the value of output per hectare. We classified all cases according to four different types of intensification: 1) reduced fallow, involving either a shortening of the fallow period or replacement of old fallow land by permanent crops[4], 2) increased input use, including greater use of labor, time, fertilizer, irrigation, seed, feed or cash[5], 3) crop changes, in particular towards cash crop production, and 4) multiple types of innovations applied in combination[6].

SUPPLEMENTARY METHODS

Search strings used

The pool of research that employs an ecosystem service framework to explore both social and ecological outcomes of agricultural intensification is quite recent and modest in size. For this reason, we adopted a pragmatic sampling strategy, combining different targeted searches, to secure a sufficient and robust set of the core peer-reviewed literature. The searches took place in January and February 2017 using Web of Science and combining terms associated with 1) land use intensification in agrarian landscapes, 2) ecosystem services, and 3) well-being.

Primary Search String

TOPIC= ((agricul OR "land use") AND (intensi*) AND ("ecosystem service*" OR "environmental service*") AND (poverty OR well*being OR income OR poor OR livelihood*))*

n = 160 articles

Secondary Search Strings

The primary search string resulting in 160 papers was subsequently supplemented by targeted searches beginning with a second Web of Science search that narrowed the initial condition by requiring the phrase ‘land use intensification’ or ‘agricultural intensification’ in the title, but then broadened subsequent conditions by connecting ecosystem service and well-being terms with an ‘or’ operator (replacing ‘and’). After removing duplicates, this added a further 95 papers.

TITLE= ("agricul* intensi*" OR "land use intensi*") AND TOPIC= ("ecosystem service*" OR "environmental service*")
TITLE= ("agricul* intensi*" OR "land use intensi*") AND TOPIC: (poverty OR well*being OR income OR poor OR livelihood*))

n = 95 articles

Selection criteria

We used four inclusion criteria to keep papers that:

1. Explicitly documented processes of agricultural intensification
2. Dealt with changes in one or more of the Millennium Ecosystem Assessment (MA, 2005) ecosystem service categories
3. Assessed changes in the overall well-being or some constituents of well-being of people dependent on agricultural intensification
4. Had a geographic focus on low or middle-income countries (c.f. World Bank 2017)

Of the 255 articles initially identified, 42 met all four of the above four criteria. We then conducted two targeted searches, reaching a point of diminishing returns at which we were satisfied we had captured much of the core literature. First, we searched the reference sections of two seminal synthesis papers on the impacts of agricultural intensification in tropical forest-agriculture landscapes: a global meta-analysis[4] and a systematic review focused on Southeast Asia[7]; second, we targeted research on the links between ecosystem services and poverty, initially through the reference section of a review of the empirical linkages by Suich et al.[8], and then using the publications database of the UK-based Ecosystem Services for Poverty Alleviation (ESPA) 10 year research programme (http://www.espa.ac.uk/results/publications). These additional sets of searches, filtered using the same four inclusion criteria, yielded 11 additional papers, resulting in a total of 53 papers reporting both social and ecosystem service outcomes of agricultural intensification across 60 specific cases. A case was constituted by the lowest geographical level at which authors presented results for different types of intensification. For example, the reporting of aggregate outcomes across multiple geographical locations was coded as one case, whereas data broken down either per distinctive type of intensification or per geographical location within one reviewed paper was coded as multiple cases.

Coding procedure

For each case, we used a pre-determined scoring code to independently assess information on: a) publication year, b) methodological approach and timescale considered, c) geographic region of the case study, d) site characteristics, e) type and definition of intensification process, f) agricultural product(s) in focus, g) factors enabling and/or constraining the intensification, h) primary intensification actors, i) other drivers of ecosystem service and well-being change that were addressed, j) impacts on ecosystem services, and k) impacts on well-being. Impacts on ecosystem services were disaggregated with primary subcomponents of provisioning services (which we divided into food and non-food), regulating services and cultural services, as well as biodiversity and supporting services. Because of the diversity of methods and approaches used in the cases, quantitative comparison of the same ecosystem service or well-being aspect within and across cases was not possible and we therefore coded impacts as positive, negative, or ambiguous through the knowledge and best available expert judgement by the coders. When impacts were recorded in multiple directions for different subcategories, the aggregate direction of ecosystem service change was taken as the overall indicator for analysis, while a tie between e.g. positive and negative impacts was coded as an ambiguous result. Impacts on human well-being were recorded across 10 variables derived from multidimensional well-being frameworks[9,10] and categorised for analysis into two primary subcomponents of economic and non-economic well-being, with the former restricted to income measures and the latter integrating a range of less frequently measured outcomes e.g., education and employment.

Following a piloting phase designed to check the coding form and to harmonise coding practice between three coders, each case was coded by a single researcher. Following coding of all cases, the coders used their overview of the research to produce subjective, expert assessments of their level of confidence in outcomes recorded for different categories of ecosystem services and human well-being. A very low level of evidence strength (Main manuscript, Figure 2) suggests that assessment is often anecdotal, whilst a high level reflects robust evidence.

Meta-data

The number of published articles on joint social-ecological outcomes of agricultural intensification increased rapidly in recent years, with peak publication rates in 2015 and 2016 (Supplementary Figure 1a). The majority of cases rested on a mix of quantitative and qualitative approaches (n=40), while fewer cases relied on only a quantitative (n=18) or qualitative approach (n=2). The most common methodological approach is longitudinal (n=23), followed by 'space-for-time substitution' (n=17) and a model-based design (n=10) (Supplementary Figure 1b). Farmers were the primary intensification actors in the majority of cases (n=33), whilst national and regional policies initiated intensification processes in 13 and 3 of the cases, respectively. Not all cases described intensification actors.

Locational variables expected to influence outcomes

In addition to the variables included in the coding protocol, we examined a number of other factors expected to be associated with social-ecological outcomes. Firstly, as a proxy for prevailing land use intensity, we extracted the mean Human Influence Index (HII)[11] for the 3rd level administrative unit in which the case lies. The mean for the 2nd admin unit was used in cases where the 3rd level was missing. The HII is a relative score from 1-100 that integrates information on human population pressure, land use and infrastructure and human access for the period 1995-2004. It provides a relative indicator of land use intensity normalised for each biome. We observe that across the three most common types of social-ecological outcomes, the median score is lowest for the 'win-win' cases (25.8) and highest for the 'lose-lose' cases (32.2), with 'win-lose' cases having a median score of 31.1 (Supplementary Figure 2a and 3). Secondly, data of tree cover and tree cover loss was extracted from the Hansen et al.[12] dataset, at subnational level and using a forest threshold definition of >20% tree cover. Forest cover was extracted for the year 2000 as we were interested in pre-existing forest cover and because the year 2000 was the earliest available year with data. Moreover, the bulk of papers were published after 2000 which also represents the start of the Millennium Ecosystem Assessment[8]. Forest loss was accordingly assessed for the period 2001-2015. These measures were also used as proxies for land use intensity. For both forest cover (Supplementary Figure 2c) and forest loss (Supplementary Figure 2d), we see the highest median for 'lose-lose' cases. That is, a median forest cover of 57% in 2000 and a median average annual forest loss during the period 2001-2015 of 0.38%. The picture is more blurred across the other eight social-ecological outcome categories, but with 'win-win' cases taking place in areas with a median forest cover of 40% and a median deforestation rate of 0.28%. Thirdly, to proxy the social context, we extracted the Human Development Index (HDI) from a new global gridded dataset available at 5 arc-min resolution[13,14] with sub-national data covering 39 countries and 66% of global population in 2015. HDI is a composite index of average achievement in key dimensions of human development (dimensionless indicator between 0 and 1). Data was extracted for the year 2000 to assess pre-existing social conditions that might influence the outcomes of agricultural intensification (Supplementary Figure 2b).

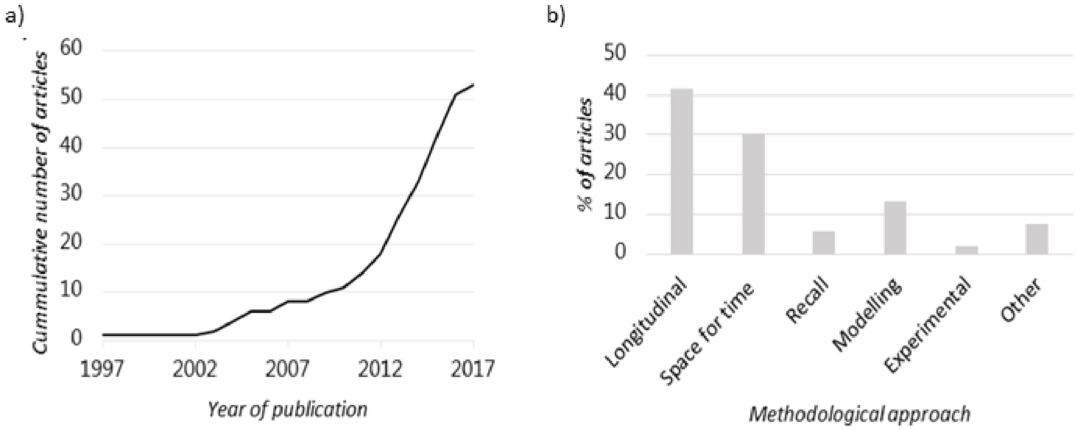
We observe the highest median HDI in 'lose-lose' cases (0.64), whereas the median score for 'win-win' cases is 0.54. A comparison of the median scores for 'win-win' and 'lose-lose' cases across the four locational variables is shown in Supplementary Figure 3. There is a significant difference in initial forest cover between 'win-win' and 'lose-lose' cases as determined by one-way analysis of variance (ANOVA) (F (1,19) = 3.2, $p <$ 0.1), whereas none of the other differences are statistically significant.

Other factors under scrutiny

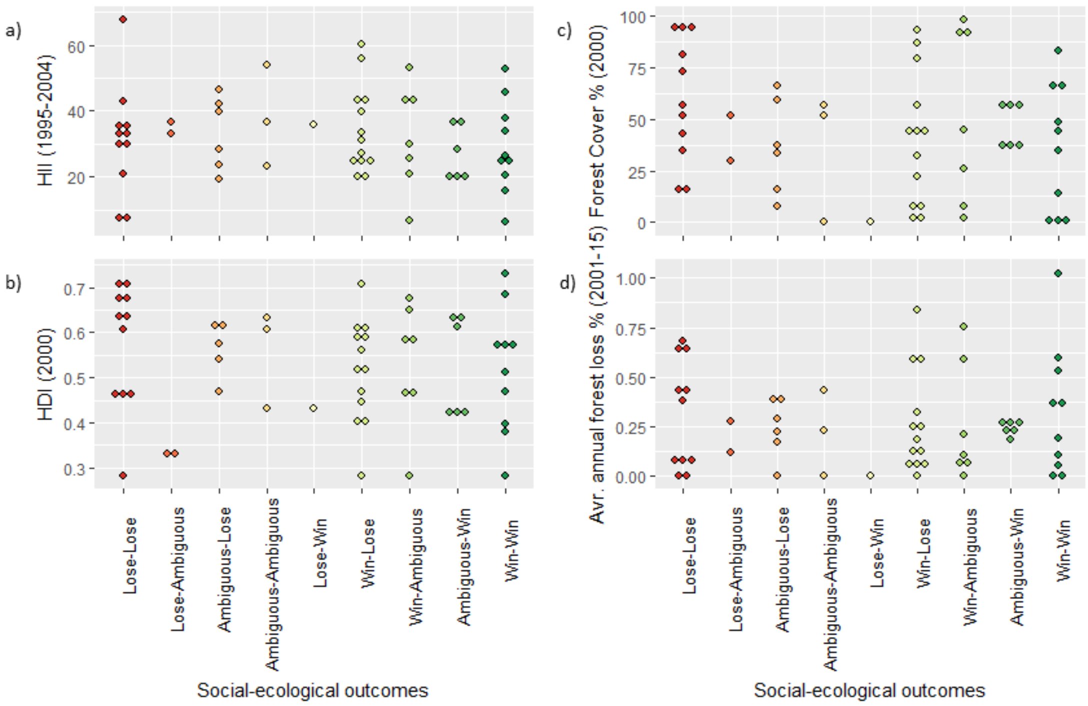
We examined whether the timescale considered in each case might influence the social-ecological outcomes reported (Supplementary Figure 4a). We see that both 'lose-lose' and 'win-win' outcomes are reported in cases assessing a multitude of different time periods, ranging from less than five years to more than 20 years. Both 'lose-lose' and 'win-win' outcomes are likewise reported by cases adopting a space-for-time approach. Analogously, we observe that the most likely type of outcome to occur ('win-lose') is also reported across cases with different timescales. Yet, half of the 'win-lose' cases assess a period of more than 20 years, whereas only 27% of the total number of cases look at more than 20 years. None of the 'win-lose' cases consider less than five years.

We observe that cases reporting 'lose-lose' and 'win-win' outcomes span across multiple approaches, including a space-for-time substitution, longitudinal studies, model-based designs, and recall studies (Supplementary Figure 4b). More than half of the 'win-lose' cases adopt a longitudinal design, which is also the most commonly adopted across all cases.

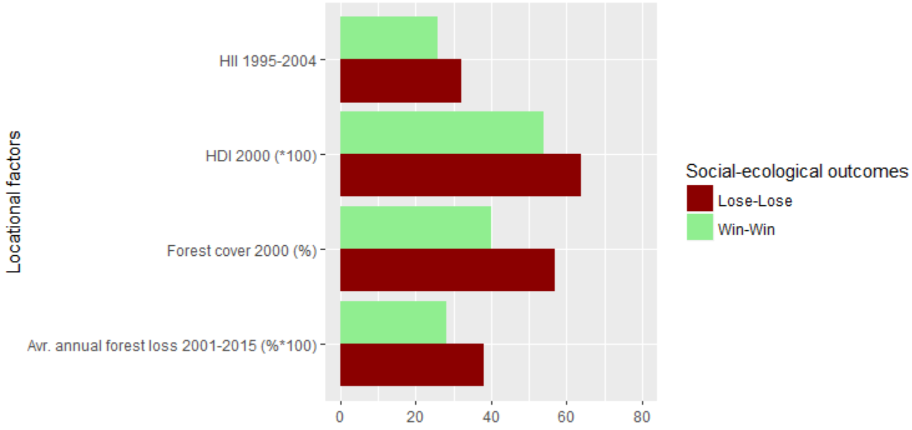
SUPPLEMENTARY FIGURES



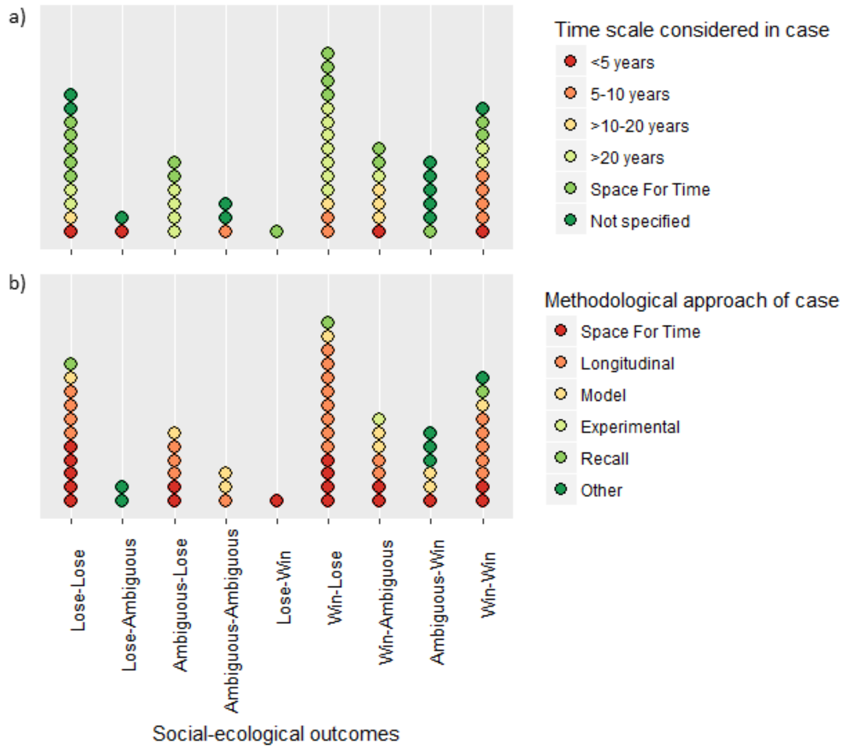
Supplementary Figure 1. a) Cumulative number of articles published during the period 1997–2017 and b) methodological approach used in articles (n = 53)



Supplementary Figure 2. Joint outcomes of agricultural intensification for well-being and ecosystem services related to a) the Human Influence Index (HII), b) the Human Development Index (HDI), c) Forest cover in 2000, and d) Average annual forest loss during the period 2001-2015. a,c,d: n=59 cases, b: n=58 cases (Ceddia et al.[15] is omitted from a-d as the case describes aggregate results across six countries, whereas Lavelle et al.[16] is also omitted from b as the paper presents aggregate results across two countries representing one biome).



Supplementary Figure 3. Median scores for the Human Influence Index (HII), the Human Development Index, forest cover in 2000, and average annual forest loss during the period 2001-2015 for those cases on agricultural intensification describing 'lose-lose' (n=11) and 'win-win' (n=10) outcomes.



Supplementary Figure 4. Joint outcomes of agricultural intensification for well-being and ecosystem services across a) timescales considered and b) methodological approaches adopted (n=60 cases).

SUPPLEMENTARY TABLES

Supplementary Table 1. List of 53 articles included in the review

Authors	*Paper Title*	*Publication Year*
Adams & Mortimore	Agricultural intensification and flexibility in the Nigerian Sahel	1997
Alvez et al.	Transition from Semi-Confinement to Pasture-Based Dairy in Brazil: Farmers' View of Economic and Environmental Performances	2014
Aragona & Orr	Agricultural Intensification , Monocultures, and Economic Failure: The Case of Onion Production in the Tipajara Watershed on the Eastern Slope of the Bolivian Andes	2011
Agoramoorthy et al.	India's women-led vegetable cultivation improves economic and environmental sustainability	2012
Belsky & Siebert	Cultivating cacao: implications of sun-grown cacao on local food security and environmental sustainability.	2003
Berg et al.	Integrated Rice-Fish Farming: Safeguarding Biodiversity and Ecosystem Services for Sustainable Food Production in the Mekong Delta	2012
Boerner et al.	Ecosystem services, agriculture, and rural poverty in the eastern Brazilian Amazon: Interrelationships and policy prescriptions	2007
Briske et al.	Strategies to alleviate poverty and grassland degradation in inner Mongolia	2015
Brown et al.	Use of provisioning ecosystem services drives loss of functional traits across land use intensification gradients in tropical forests in Madagascar	2013
Cardozo et al.	Species richness increases income in agroforestry systems of eastern Amazonia	2015
Castella et al.	Effects of Landscape Segregation on Livelihood Vulnerability: Moving From Extensive Shifting Cultivation to Rotational Agriculture and Natural Forests in Northern Laos	2013
Ceddia et al.	Sustainable agricultural intensification or Jevons paradox? The role of public governance in tropical South America	2013
Clough et al.	Combining high biodiversity with high yields in tropical agroforests	2011
Dahal et al.	Agricultural intensification: food insecurity to income security in a mid-hill watershed of Nepal	2009
Dawson et al.	Green Revolution in Sub-Saharan Africa: Implications of Imposed Innovations for the Well-being of Rural Smallholders	2016
Dearing et al.	Safe and just operating spaces for regional social-ecological systems	2014
Dearing et al.	Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin	2012
Dile et al.	Assessing the implications of water harvesting intensification on upstream-downstream ecosystem services: A case study in the Lake Tana basin	2016
Fu et al.	Smallholder rubber plantation expansion and its impact on local livelihoods, land use and agrobiodiversity, a case study from Daka, Xishuangbanna, southwestern China.	2009
Hengsdijk	Poverty and biodiversity trade-offs in rural development: a case study for Pujiang county, China	2007
Hulme et al.	Conserving the Birds of Uganda's Banana-Coffee Arc: Land Sparing and Land Sharing Compared	2013
Hossain et al.	Unravelling the interrelationships between ecosystem services and human well-being in the Bangladesh delta	2017
Hossain et al.	Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone	2016
Isaacs et al.	Assessing the value of diverse cropping systems under a new agricultural policy environment in Rwanda	2016
Islam et al.	Implications of agricultural land use change to ecosystem services in the Ganges delta	2015
Jacovak et al.	Swiddens under transition: Consequences of agricultural intensification in the Amazon	2016
Jakovac et al.	Loss of secondary-forest resilience by land-use intensification in the Amazon	2015
Karlberg et al.	Tackling Complexity: Understanding the Food-Energy-Environment Nexus in Ethiopia's Lake Tana Sub-basin	2015
Karp et al.	Forest bolsters bird abundance, pest control and coffee yield	2013
Krupnik et al.	Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential	2017
La Rovere	Co-evolutionary scenarios of intensification and privatization of resource use in rural communities of south-Western Niger	2005
Lavelle et al.	Unsustainable landscapes of deforested Amazonia: An analysis of the relationships among landscapes and the social, economic and environmental profiles of farms at different ages following deforestation	2016
Lusiana et al.	Land sparing or sharing? Exploring livestock fodder options in combination with land use zoning and consequences for livelihoods and net carbon stocks using the FALLOW model	2012
Marquardt et al.	Farmers' Perspectives on Vital Soil-related Ecosystem Services in Intensive Swidden Farming Systems in the Peruvian Amazon	2013
Nadal & Rano	Environmental Impact of Changes in Production Strategies in Tropical Mexico	2011

Okubo et al.	Traditional perennial crop-based agroforestry in West Java: the tradeoff between on-farm biodiversity and income	2010
Rahman et al.	Towards productive landscapes: Trade-offs in tree-cover and income across a matrix of smallholder agricultural land-use systems	2016
Renwick et al.	Achieving production and conservation simultaneously in tropical agricultural landscapes	2014
Riwthong et al.	Land use intensification, commercialisation and changes in pest management of smallholder upland agriculture in Thailand	2015
Seck et al.	Senegal Adaptation and Mitigation Through “Produced Environments”: The Case for Agriculture Intensification in Senegal	2005
Semwal et al.	Patterns and ecological implications of agricultural land-use changes: a case study from central Himalaya, India	2004
Shaver et al.	Coupled social and ecological outcomes of agricultural intensification in Costa Rica and the future of biodiversity conservation in tropical agricultural regions	2014
Shively & Pagiola	Agricultural intensification, local labor markets, and deforestation in the Philippines	2004
Szabo et al.	Soil salinity, household wealth and food insecurity in tropical deltas: evidence from south-west coast of Bangladesh	2015
Tadesse et al.	Prospects for forest-based ecosystem services in forest-coffee mosaics as forest loss continues in southwestern Ethiopia	2014
Wagner et al.	Drivers and consequences of land use patterns in a developing country rural community	2015
Wood et al.	Intensification of tropical fallow-based agriculture: Trading-off ecosystem services for economic gain in shifting cultivation landscapes?	2016
Van der Horst et al.	The hedgification of maizescapes? Scalability and multifunctionality of Jatropha curcas hedges in mixed farming landscape in Zambia	2014
VanWey et al.	Socioeconomic development and agriculture in Mato Grosso	2013
Xu et al.	Effects of land-use intensity on ecosystem services and human well-being: a case study in Huailai County, China	2016
Yin et al.	The implementation and impacts of China's largest payment for ecosystem services program as revealed by longitudinal household date	2014
Zimmerer	The compatibility of agricultural intensification in a global hotspot of smallholder agrobiodiversity (Bolivia)	2013
Zhang et al.	Poverty alleviation strategies in eastern China lead to critical ecological dynamics	2015

SUPPLEMENTARY REFERENCES

1 Millenium Ecosystem Assessment. Ecosystems and Human Well Being, Synthesis. Island, Washington, DC. (2005).

2 Wall, D. H. & Nielsen, U. N. Biodiversity and ecosystem services: is it the same below ground. *Nature Education Knowledge* **3** (2012).

3 Kaimowitz, D., Byron, R. N. & Sunderlin, W. D. *Public policies to reduce inappropriate tropical deforestation*. Earthscan (2005).

4 van Vliet, N. *et al.* Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. *Global Environmental Change* **22**, 418-429, doi:10.1016/j.gloenvcha.2011.10.009 (2012).

5 FAO. The ethics of sustainable agricultural intensification. Rome: Food and Agriculture Organization of the United Nations. (2004).

6 Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 20260-20264, doi:10.1073/pnas.1116437108 (2011).

7 Dressler, W. H. *et al.* The impact of swidden decline on livelihoods and ecosystem services in Southeast Asia: A review of the evidence from 1990 to 2015. *Ambio* **46**, 291-310, doi:10.1007/s13280-016-0836-z (2017).

8 Suich, H., Howe, C. & Mace, G. Ecosystem services and poverty alleviation: A review of the empirical links. *Ecosystem Services* **12**, 137-147, doi:https://doi.org/10.1016/j.ecoser.2015.02.005 (2015).

9 Alkire, S. & Santos, M. E. Measuring Acute Poverty in the Developing World: Robustness and Scope of the Multidimensional Poverty Index. *World Development* **59**, 251-274, doi:10.1016/j.worlddev.2014.01.026 (2014).

10 Nussbaum, M. Creating Capabilities. *Harvard University Press* (2011).

11 Wildlife Conservation Society & Center for International Earth Science Information Network. Last of the Wild Project, Version 2, 2005 (LWP-2): Global Human Footprint Dataset

(Geographic). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4M61H5F. 2005.
12 Hansen, M. C. *et al.* High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **342**, 850-853, doi:10.1126/science.1244693 (2013).
13 Kummu, M., Taka, M. & Guillaume, J. H. A. Dryad Data Repository (2018). https://doi.org/10.5061/dryad.dk1j0
14 Kummu, M., Taka, M. & Guillaume, J. H. A. Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. *Scientific Data* **5**, 180004, doi:10.1038/sdata.2018.4https://www.nature.com/articles/sdata20184#supplementary-information (2018).
15 Ceddia, M. G., Sedlacek, S., Bardsley, N. O. & Gomez-y-Paloma, S. Sustainable agricultural intensification or Jevons paradox? The role of public governance in tropical South America. *Global Environmental Change* **23**, 1052-1063, doi:https://doi.org/10.1016/j.gloenvcha.2013.07.005 (2013).
16 Lavelle, P. *et al.* Unsustainable landscapes of deforested Amazonia: An analysis of the relationships among landscapes and the social, economic and environmental profiles of farms at different ages following deforestation. *Global Environmental Change* **40**, 137-155, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.009 (2016).