



Do provisioning ecosystem services change along gradients of increasing agricultural production?

Ronju Ahammad · Stephanie A. Tomscha · Sarah E. Gergel · Frédéric Baudron · Jean-Yves Duriaux-Chavarría · Samson Foli · Davidson Gumbo · Dominic Rowland · Josh van Vianen · Terry C. H. Sunderland

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Abstract

Context Increasing agricultural production shapes the flow of ecosystem services (ES), including provisioning services that support the livelihoods and nutrition of people in tropical developing countries. Although our broad understanding of the social-ecological consequences of agricultural intensification

is growing, how it impacts provisioning ES is still unknown.

Objectives We examined the household use of provisioning ES across a gradient of increasing agricultural production in seven tropical countries (Bangladesh, Burkina Faso, Cameroon, Ethiopia, Indonesia, Nicaragua and Zambia). We answered two overarching questions: (1) does the use of provisioning ES differ along gradients of agriculture production ranging from zones of subsistence to moderate and to high

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R. Ahammad (✉)
Research Institute for the Environment and Livelihoods,
Charles Darwin University, Darwin, NT 0810, Australia
e-mail: ronju.ahammad@cdu.edu.au

S. A. Tomscha
School of Biological Sciences, Victoria University
of Wellington, PO Box 600, Wellington 6140,
New Zealand

S. E. Gergel · T. C. H. Sunderland
Faculty of Forestry, University of British Columbia, 2424
Main Mall, Vancouver, V6T 1Z4, Canada

F. Baudron
International Maize and Wheat Improvement Center
(CIMMYT), Southern Africa Regional Office, PO Box
MP163, Mt Pleasant, Peg Mazowe, Harare, Zimbabwe

F. Baudron
Centre de coopération internationale en recherche
agronomique pour le développement (CIRAD), Avenue
Agropolis, 34398 Montpellier Cedex 5, France

J.-Y. Duriaux-Chavarría
Conservation Ecology Group, University of Groningen,
PO Box 72, 9700 AB, Groningen, The Netherlands

S. Foli
Plant Production Systems, Wageningen University, PO
Box 9101, 6700 HB, Wageningen, The Netherlands

D. Gumbo
Centre for International Forestry Research, PO Box 50977,
Ridgeway, Lusaka, Zambia

D. Rowland
Centre for Development, Environment and Policy
(CeDEP), SOAS University of London, 10 Thornhaugh St,
WC1H 0XG, London, UK

J. van Vianen
Sustainability Tech, Telaga Waja No.28, Renon, Denpasar
Selatan, 80234 Kota Denpasar, Bali, Indonesia

T. C. H. Sunderland
Centre for International Forestry Research, Jalan CIFOR
Situ Gede, 16115 Bogor, Indonesia

agriculture production? and (2) are there synergies and/or trade-offs within and among groups of ES within these zones?

Methods Using structured surveys, we asked 1900 households about their assets, livestock, crops, and collection of forest products. These questions allowed us to assess the number of provisioning ES households used, and whether the ES used are functionally substitutable (i.e., used similarly for nutrition, material, and energy). Finally, we explored synergies and trade-offs among household use of provisioning ES.

Results As agricultural production increased, provisioning ES declined both in total number and in different functional groups used. We found more severe decreases in ES for relatively poorer households. Within the functional groups of ES, synergistic relationships were more often found than trade-offs in all zones, including significant synergies among livestock products (dairy, eggs, meat) and fruits.

Conclusions Considering landscape context provides opportunities to enhance synergies among provisioning services for households, supporting resilient food systems and human well-being.

Keywords Agricultural production zones · Agricultural intensification · Ecosystem services · Synergies and trade-offs · Landscape multifunctionality · Social-ecological systems

Introduction

By 2050 feeding the world's projected nine billion people may require the addition of 2.7–4.9 Mha of agricultural land per year and will result in additional pressures on forests (Godfray et al. 2010, Godfray and Garnett 2014; Lambin and Meyfroidt 2011). Globally, agriculture remains the largest single driver of deforestation (Curtis et al. 2018; DeFries et al. 2010). In tropical regions, land for new agriculture is often derived from forests and other areas of natural vegetation, including old-growth forests, woodlands, and semi-arid environments (Gibbs et al. 2010; Laurance et al. 2014). Agricultural expansion and intensification of existing farmland are pervasive features of our current food security narrative and food systems, that have homogenised global diets and reduced the role of diverse ecosystems, including forests and trees, in maintaining dietary diversity and nutrition

(Bahar et al. 2020; Gergel et al. 2020; HLPE 2017; Ickowitz et al. 2022; Rasolofson et al. 2018). Concomitantly, our food systems have compromised the multi-functionality of landscapes through the conversion of natural ecosystems to mainly monoculture agriculture (Clark et al. 2014; DeFries et al. 2015; Duriaux-Chavarría et al. 2021; Johns and Eyzaguirre 2006; Khoury et al. 2014; Mastrangelo et al. 2014).

Agricultural expansion and intensification have substantial implications for ecosystem services (ES) (i.e., the benefits people derive from nature) at both local and global scales (Tilman 1999; Power 2010; Adams 2014; Rasmussen et al. 2018; Baudron et al. 2021). Due to agricultural change, strong evidence exists on synergies and trade-offs within the broad ecosystem services categories, i.e., between provisioning services—such as food production—and a range of regulating and supporting services such as water purification, nutrient cycling and carbon storage globally (Foley et al. 2005; Ayala et al. 2016). Studies on trade-offs and synergies among distinct provisioning services groups that contribute differently to livelihood, nutrition and well-being lag (Berry et al. 2020; Reed et al. 2017). Provisioning ES meet the diverse needs for calories, nutrition, material, and energy of many millions of people to achieve their well-being, in particular in the developing tropics (MA 2005; Clark et al. 2014; Dhyani and Dhyani 2016; Adams et al. 2018; Ahammad et al. 2019a; Fedele et al. 2021; Karimi and Raymond 2022). Different provisioning ES groups have distinct contributions, e.g., legumes, vegetables, and meat, on dietary and nutrition, whereas construction timber and fuel wood are for material needs. On the other hand, some ES groups support maintaining substitutive functions, e.g., plant and animal proteins (Allen et al. 2014; Weerasekara et al. 2020). Food, material and energy needs are affected by changes in the diversity of provisioning ES groups associated with the agricultural changes in the tropics.

Some studies suggest the outcomes of agricultural change, e.g., transition from subsistence farming to commercial agriculture, result in increased socio-economic opportunities through income-oriented activities improving people's economic capacity (Ickowitz et al. 2016; Broegaard et al. 2017; Castella et al. 2013; Castle et al. 2021). Alternatively, this process causes externalities to social-ecological systems by lessening the option for bio-diverse land uses and the associated

flow of ES to Indigenous people and local communities (Mathys et al. 2023). The intensive land use with simplification of farmed landscape alters ES's availability and diverse functional groups required to fulfil dietary, nutrition and material needs, among others. However, the changes within and among provisioning ES supply have yet to be widely explored along gradients in a landscape (Tadesse et al. 2014). Until recently, monetary valuation, spatial and temporal assessment of synergies and trade-offs of broad ES from land uses have been common to estimate ES values in general (e.g., Costanza et al. 1997; Sutton and Costanza 2002; Nelson et al. 2009; Qiu and Turner 2013). We have a very limited understanding of how increased agricultural production mediates the availability and diversity of provisioning ES groups to distinct user groups of socio-economic conditions along gradients of landscape simplification and agricultural intensification (Sunderland et al. 2017; Balzan et al. 2018; Ferreira et al. 2021). We assume that the patterns of use of the types of provisioning ES differ within the households of different wealth conditions located alongside such gradients.

People benefit from and perceive the value of ES differently, reflecting social differentiation regarding the influence of wealth conditions, ethnicity and locations in a landscape (Daw et al. 2011; Ahammad et al. 2019a). Investigating how wealthy groups value and prioritize ES differently is crucial to understanding what matters to whom and interrogating dominant narratives of agrarian changes and ES outcomes. The provisioning services used or gathered for livelihoods do not always represent equally demanding within the households of different asset conditions (Lau et al. 2018). Little monetary value of specific goods, such as wild foods gathered for direct consumption, remain crucial for the poorer group than wealthier households and may not be an important consideration by policymakers in decision-making. Besides, the perceptions of the landscape changes in terms of forest loss and any form of land use intensification or commercialisation of crops and their impacts also matter in different ways to the adjacent Indigenous and local communities who experience the flow of ES differently (Ahammad et al. 2019b; Mathys et al. 2023). The highly wealthy group in the agrarian society may find alternative use of ES either through income sourced from timber harvesting from plantation or commercial crops; however, the livelihoods of the

poor are not as rewarding as the former, as the latter only receive the minimal economic return (Paumgarten and Shackleton 2009; Andersson et al. 2018). Assessing and disaggregating both the use of ES is a useful tool for gaining a broader sense of what different and diverse wealthy groups might want and what they may have in common (Lau et al. 2018).

Exploring the nuanced ways people utilise provisioning ES in a landscape undergoing various stages of agricultural change is a research imperative in many tropical developing countries. With this in mind, we aimed to examine the patterns of provisioning ES used by households across a gradient of agricultural production zones in seven developing tropical countries (Bangladesh, Burkina Faso, Cameroon, Ethiopia, Indonesia, Nicaragua and Zambia). ES have numerous use values to sustain human well-being, and in our study, we considered the benefits obtained from direct use, i.e., consumptive benefits of using forest, agricultural and livestock-sourced products to entail provisioning ES (Daily 1997; Pascual et al. 2010). We answered two overarching questions: (1) does the provisioning ES use differ along the gradients of agriculture production ranging from subsistence to moderate and to high agriculture production zones (3 zones) in those countries? and (2) are there synergies and/or trade-offs within and among groups of ES along the gradients/zones? For the first question, we assessed the use patterns of total provisioning ES and their different functional groups (such as cereal, meat, legumes etc.) by household wealth and zone levels within and across seven countries. ES commonly occur in bundles (sets of services that repeatedly appear together), and certain groups of services are more accessible than others within a changing agricultural landscape (Adams et al. 2018). So in the second question, we explored the interactions of functional groups of ES by identifying synergies and trade-offs of different functional groups of ES across the three zones.

Material and methods

Approach for study site selection

Each of the seven countries possesses tropical forests under varying levels of pressure from agricultural production, often through both intensification

and expansion (Deakin et al. 2016; Sunderland et al. 2017; Figs. 1, 2). We carefully selected the study sites in each country according to the following criteria: market-oriented crop production, farming types, extent of forest cover, population density, proximity to major towns, and infrastructural development (Sunderland et al. 2017; Figs. 1, 2; Table 1). Within each country, three zones were identified reflecting a

gradient of increasing agricultural production from lower production with subsistence farming (zone 1), to intermediate agricultural production (zone 2), and finally to higher production with greater connection to markets (zone 3) (Fig. 2; Appendix 1) (Sunderland et al. 2017; Table 1). A scoping survey was conducted during 2014–2015 in each of the study locations to validate those criteria with the consultation of

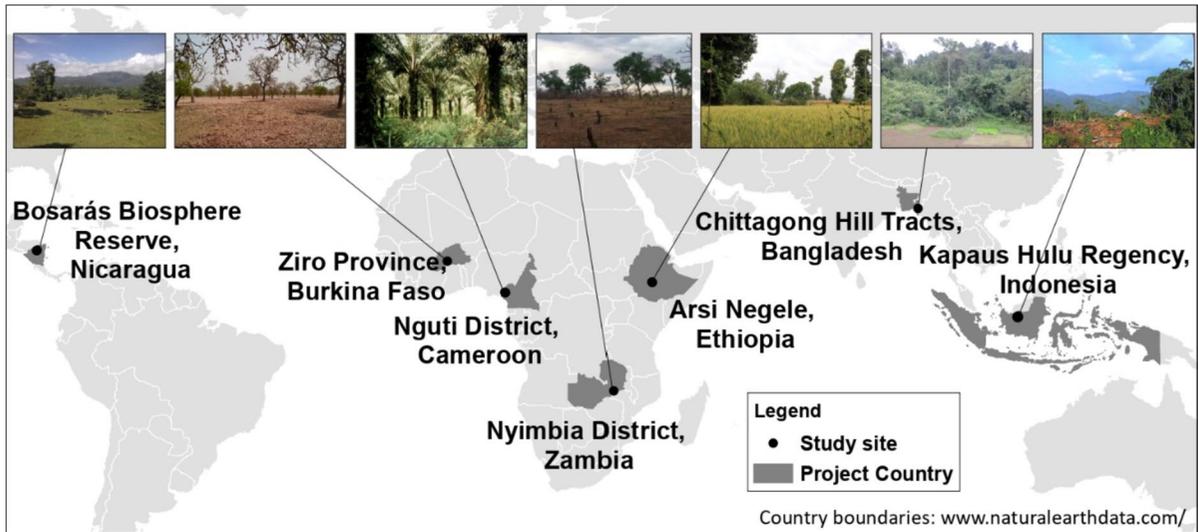


Fig. 1 Study locations in seven tropical countries, each of which is facing agricultural transitions due to loss of forest cover and increased agricultural production (often through

both intensification and expansion). Taken together, these countries represent a range of forest types, subsistence and agricultural commodities, in low-income regions

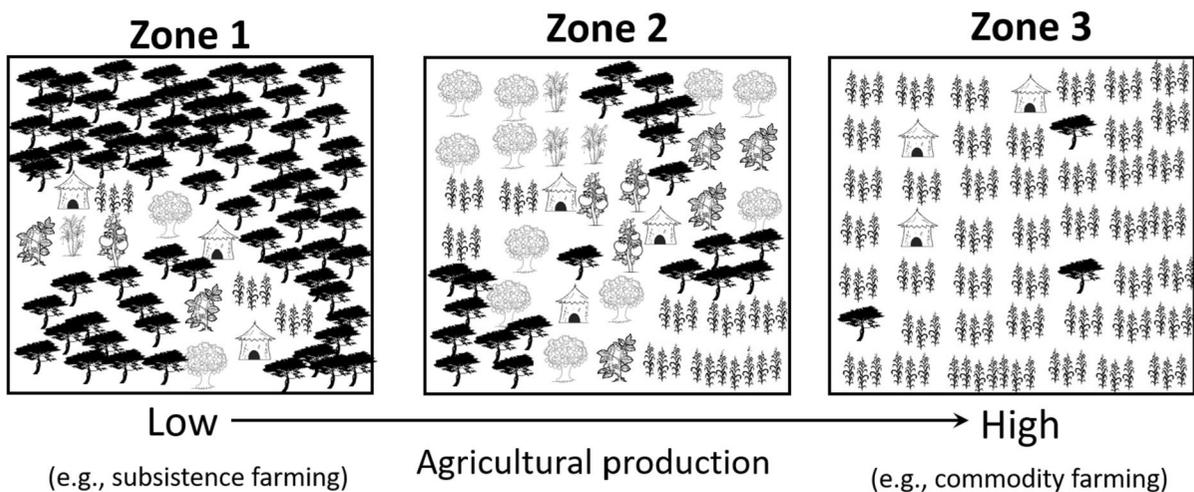


Fig. 2 Within each of the seven study countries, three contrasting zones of increasing agricultural production were studied. Detailed criteria for these zones are explained further in Table 1

Table 1 Criteria used to guide general selection of agricultural production zones within each country. Surveys of approximately 100 randomly selected households within each of the

three zones in each country were conducted from 2015–2017, for a total of 1900 household surveys

Criteria	Zones of agricultural production		
	Lower (zone 1)	Intermediate (zone 2)	Higher (zone 3)
Market oriented crop production	Rare	Occasional	Common
Presence of subsistence farming	High	Medium	Low
Proximity to forest (e.g., protected areas)	Near	Far	Distant
Population density	Sparse	Medium	Dense
Proximity to major towns	Distant	Far	Near
Levels of infrastructure development	Low	Moderate	High

government and non-government personnel and local communities to delineate and describe each zone (Deakin et al. 2016).

In Bangladesh, twelve villages across three sub-districts of two districts (Rangamati and Bandarban) in the Chittagong Hill Tracts region of Bangladesh were selected (Fig. 1) (Ahhammad and Stacey 2016). The land cover follows a transition from largely swidden farming and natural forests in the remote villages of the landscape to mixed agroforests with understorey crops, monocultures of fruit, timber and other trees in the intermediate zone (Ahhammad et al. 2021). More settled agricultural land uses with cash crops (mainly ground nuts, potato, vegetables and tobacco), monoculture trees with mainly teak (*Tectona grandis*) and Gamar (*Gmelina arborea*) as well as home gardens is evident along the highest agricultural production zone.

In Burkina Faso, nine villages across 3 districts (Bakata, Cassou and Gao) in Ziro Province of central Burkina Faso were selected (Fig. 1). The landscape is a typical Sahelian managed agroforestry parkland dominated by trees species such as shea (*Vitellaria paradoxa*), baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) (Foli and Abdoulaye 2016). Land-use transitions range from exploitation of forest products, fuelwood, and agro-pastoralism to cereal and cotton monoculture along the agricultural production gradient.

In Cameroon, four focal villages in the Nguti district were selected (Fig. 1). Natural vegetation in the region is comprised of Atlantic Biafra forest and is rich in biodiversity. Primary land use consists of subsistence swidden fallow agriculture, producing mainly cocoyams, plantains, cassava and bananas for

subsistence, and oil palm, coffee, and cocoa as cash crops (Asaha and Deakin 2016).

The Ethiopia study site covered three pairs of villages corresponding to three zones of increasing distance to the state-owned Munessa Forest and decreasing distance to the urban center of Arsi Negele (Fig. 1). Tree cover and crop diversity decreased with increasing distance to the forest, but otherwise the zones were similar in all other social and ecological variables. The farms are generally small (i.e., less than 3 ha) and rely on crop and livestock production, with wheat (*Triticum aestivum*), maize (*Zea mays*), potato (*Solanum tuberosum*), cattle (*Bos indicus*) and sheep (*Ovis aries*) as the most important species (Baudron et al. 2019).

In Indonesia, eight villages across three sub-districts in Kapuas Hulu Regency, West Kalimantan (Fig. 1) (Leonald and Rowland 2016). The landscape ranged from remote forest dependent communities, primarily engaged in swidden agriculture, collection of commercial NTFPs and artisanal gold mining through to oil palm growing communities consisting of contract-smallholders, independent smallholders and waged plantation labourers. Rubber (*Hevea brasiliensis*), grown in mixed-agroforestry gardens, often combined with fruit and nut trees, is a common transitional crop between swidden, with rice, and oil palm (*Elaeis guineensis*).

The Nicaragua site included six villages at different distances from the Saslaya National park within the Bosawás Biosphere Reserve (Fig. 1). The agricultural production includes maize (*Zea mays*), rice (*Oryza sativa*), beans (*Phaseolus vulgaris*), coffee (*Coffea arabica*), cacao (*Theobroma cacao*) and cattle (*Bos indicus*; *Bos taurus*) production. The different

farm size (from less than 1 ha to over 100 ha) creates a dynamic agricultural labour market, and other forms of non-agricultural labour are also common, especially near the main roads.

In Zambia, 3 villages located in the Nyimba District of Zambia's Eastern Province were selected (Fig. 1). The landscape is dominated by miombo woodlands, where trees of genera *Brachystegia*, *Isoberlinia* and *Julbernardia* dominate. Land-use transitions range from widespread encroachment on the forests, harvesting of forest products e.g., fuelwood (charcoal and fuelwood), forests foods such as mushrooms to the growing of maize (*Zea mays*) and cotton (*Gossypium* spp) (Gumbo et al. 2016). Maize is widely grown and some years with government subsidies while cash crops such as cotton and tobacco (*Nicotiana tabacum*) are grown through private sector support. The level of agricultural production varies by source and costs of key inputs.

Data collection

Household surveys were conducted to collect qualitative and quantitative data in the three zones of each country. Between 2015 and 2017, in each of the three zones across the seven study countries, approximately 100 households (total 1900) were randomly sampled and surveyed (Sunderland et al. 2017). Random sampling was achieved using a list of households from local censuses or election records. Where census data was not available, households were identified using aerial photographs. The survey questions centred on the variety of ways people benefitted from landscapes in different zones/sites, including forest- and tree-based land uses (Deakin et al. 2016; Sunderland et al. 2017). We asked structured questions to the respondents on their household assets used for domestic, production and transportation purposes, livestock ownership, crop production and the gathering of forest products, all in the local languages of each site, as relevant.

Related to provisioning ES uses, the three main questions included in the surveys were: 1) which forest products have your household collected in the last 12 months? Here, participants selected from a list of forest products developed through a scoping study for each country (Deakin et al. 2016); 2) how many livestock of different species are currently owned by your household? Participants were provided with a list of

20 different livestock species relevant to the local conditions of each country and were asked to identify the ones relevant to their household; and 3) which crops were grown on the farm's fields in the last 12 months. Either the head of the household, or a respondent over 18 years old was interviewed from each household. In our surveys, the households reported the presence/absence of crops (yes/no), livestock ownership (number), products used, and forest products gathered (yes/no) in the last 12 months.

The households surveyed reported using a total of 207 provisioning ES (i.e., 165 crop species, 26 livestock species and 16 forest products) across the three zones in the seven countries. These ES represented 18 different functional groups (i.e., beverage and spices, legumes, cereals, oilseed, eggs, etc.—see details in Online Appendix 2) following the broader functional group categories of Food and Agriculture Organization (FAO 2010). For example, crops used by a household fell into the following functional groups: beverages and spices; legumes; cereals; oilseed; sugar; fruit and nuts; vegetables; tubers etc. Livestock used by households included dairy, meat, eggs and/or draught services. The uses of forest/tree products in households were categorised into fuelwood; water (gathered from a forested area); forage; fibre and dyes; ornamental plants and animals; medicines; and shade and construction materials. Due to the rarity of sugar crops, forage, as well as shade and construction materials—each of which were reported frequently in only one or two countries—we excluded these groups from further analysis, leaving 18 different groups of provisioning ecosystem services (see supplementary information).

Data analysis

Construction of household wealth indices

To characterise the surveyed households, we constructed wealth indices based on the asset ownership of individual households. Following studies that measured wealth indices (Rutstein 2008; Smits and Steendijk 2015), we considered three broad asset categories: domestic, productive and non-productive, and transport assets in wealth construction of the surveyed households. Domestic assets included the dwelling characteristics of the households, including household access to electricity, toilet conditions,

bed frame, house wall and roof construction materials, and water sources, among others. Productive assets included the type of farming tools available for cultivation and harvesting, such as axe, machete, hand hoe and livestock availability. Non-productive assets included, e.g., television and radio. Transport assets included the household's transport for their day-to-day movements, such as bicycle and motorcycle. Altogether, we considered over 70 asset variables covering the two dimensions in the surveys across the seven countries. The households reported any asset as 'present' or 'absent' in their house or any particular category of the asset they used with several options.

To construct wealth indices, we first considered asset variables that showed at least 5% and not more than 95% variations within the households surveyed in each country (Hjelm et al. 2017). After initial screening in an individual country, we obtained a minimum of 30 to a maximum of 43 asset variables (depending on the country) that complied with the abovementioned rule. Second, we coded asset variables as binary variables, with '1' for presence '0' for absence. Assets with more than two category levels were coded as separate binary variables. For instance, if a household reported using a latrine and a flushing toilet, we coded two separate binary asset variables. Third, we ran a principal component analysis (PCA) applied to binary asset variables in each country separately (Filmer and Pritchett 2001; Vyas and Kumaranayake 2006). PCA is used to reduce the dimensionality of the dataset and identifies linear combinations of the variables ('principal components', PCs) that maximize the variance in the dataset. For each country, we derived quintiles from PC1 to allocate a wealth index—ranging from 1 to 5, 1 being the 'poorest quintile' and 5 the 'wealthiest quintile' (henceforth referred as wealth groups) (Online Appendix 3).

Analysis of provisioning ES

Three statistical approaches were used, including a generalised mixed-effects models, generalised linear model and Pearson's correlations. For the first question, we conducted mixed-effects modelling to estimate wealth and zone level variations in the use of total provisioning ES and their functional groups richness across the seven countries (wealth and zone as fixed effects and country as a random effect) (Nakagawa and Schielzeth 2013; Mouchet et al. 2014).

The household data collected concerning the number of crops, forest products and livestock used were the basis for further analysis of the provisioning ES richness, functional group richness and interactions across the households at the wealth, zone and country level. Then we fitted individual country models separately, using the generalised linear model to examine the variations of ES use and their functional groups across wealth and the three agricultural production zones. In addition, we used Shannon's evenness index to calculate the evenness showing the degree of equality or even distribution of the individual ES used within each group within the households across the zones (Raudsepp-Hearne et al. 2010). Higher values of this index are related to a more even abundance of ecosystem services (i.e., equally or evenly distributed) used by households (Karimi and Raymond 2022). Finally, for the second question, we analysed the relationship between functional groups of ecosystem services to examine their co-occurrence across the agricultural production gradients using Pearson's correlations. Mixed models were analyzed using the package lme4 and generalised linear model using the R Stats package in the R statistical programme environment (Bates et al. 2015). We used the cocor package in R to determine whether the correlations varied significantly across the zones. For wealth construction we used "FactoMineR", and "factoextra" R packages in the PCA analysis.

Results

Patterns of ES use by households along agricultural production gradients

Three key patterns emerged in examining households' ecosystem services across the three zones. First, our analysis found a pattern of decline in the use of provisioning ES from the low (zone 1) to intermediate (zone 2) and high (zone 3) agricultural production zones across most of the countries (Fig. 3). The total ES use significantly declined from zone 1 to zones 2 and 3 ($P < 0.001$), as estimated in the model across seven countries (Fig. 4). Across the zones, there is a significantly low level of ES use in zone 3 (the high production zone). The cross-country analysis also corresponds to the individual country models that showed a significantly lower ES used by households

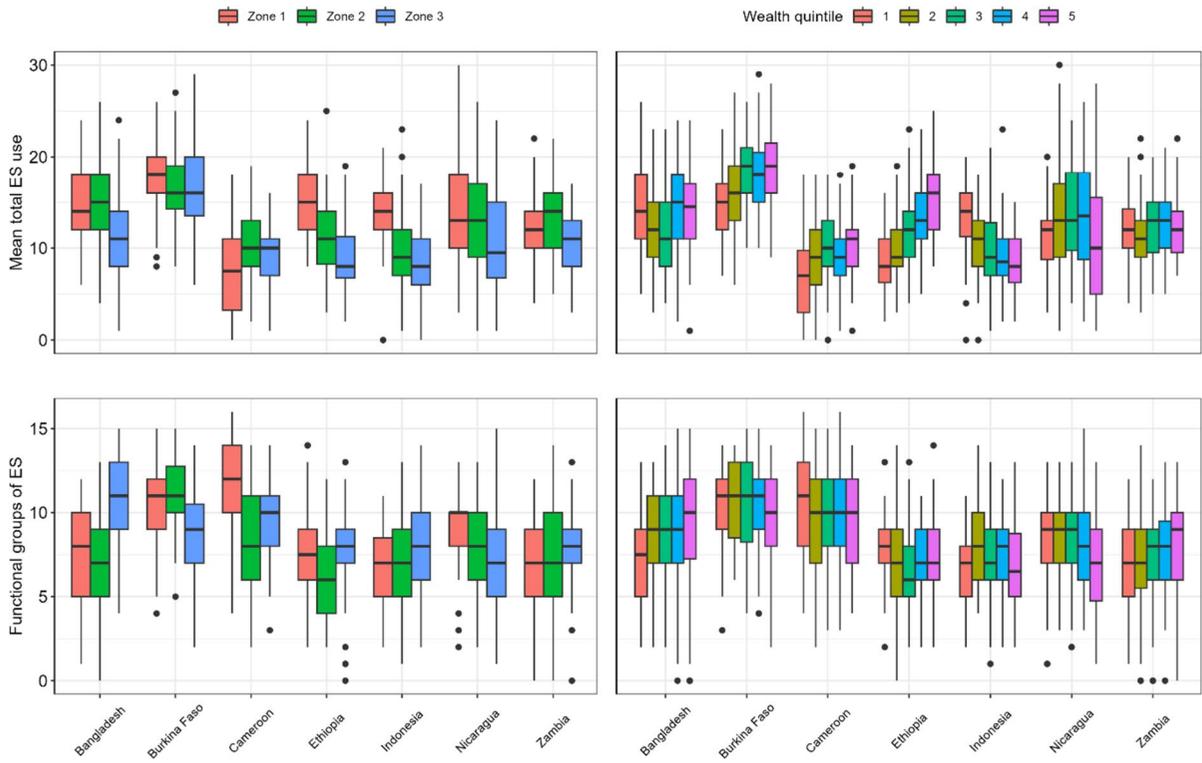


Fig. 3 Mean use of total ES and their functional groups by zones and wealth levels

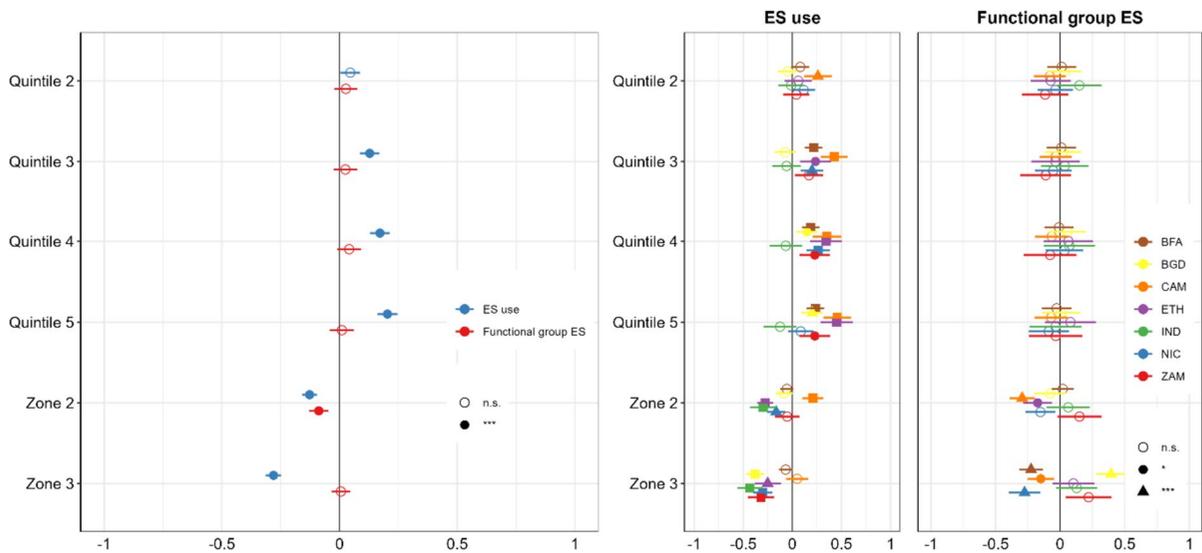


Fig. 4 Cross-country model estimates of variation in ES use and functional groups by zone and wealth levels (left). Individual country model estimates for zone and wealth level variations of the use of total ES and their functional groups (right). We reported model estimates for 95% CI and adjusted P-value

with Bonferroni correction. Significance level: $***P < 0.001$; $**P < 0.01$; $*P < 0.05$. Reference levels: Zone 1 and wealth quintile 1. Countries refer to Burkina Faso (BFA), Bangladesh (BGD), Cameroon (CAM), Ethiopia (ETH), Indonesia (IND), Nicaragua (NIC) and Zambia (ZAM)

in zone 3 ($P < 0.001$) than in zones 1 and 2 across all countries except for Cameroon (Fig. 4). In Cameroon, the household use of the richness of ES was higher in zone 2 ($P < 0.001$) than the zones 1 and 3. Household use of total provisioning ES surveyed was higher in Bangladesh, Burkina Faso, Ethiopia and Nicaragua (Fig. 3). Households reported a higher mean functional group richness in Bangladesh, Burkina Faso and Cameroon.

Second, the diversity of ES, i.e., functional groups, declined along the transition from low to high with more market-oriented agriculture. The analysis of the mean functional group of ES (i.e., the number of ES groupings in Fig. 4) showed higher in zone 1 and 3 compared to zone 2 ($P < 0.05$). Across all seven countries, the model estimates show a significantly greater number of functional groups of ecosystem services reported by households in zone 1 ($P < 0.05$) and 3 ($P < 0.05$) than in zone 2 (Fig. 4). In individual country models, a significantly higher number of ES functional groups were associated with zone 1 ($P < 0.001$) compared to zone 3 for all countries except Ethiopia (Fig. 4). In Cameroon and Nicaragua, the number of functional groups used in zone 1 was significantly higher ($P < 0.05$) than in zones 2 and 3. Conversely, in Burkina Faso, households reported significantly higher functional richness in zones 1 and 2 than in zone 3 ($P < 0.05$).

Third, the number of ES used by households (i.e., ES richness) was significantly higher within the wealthy households of the three top wealth quintiles

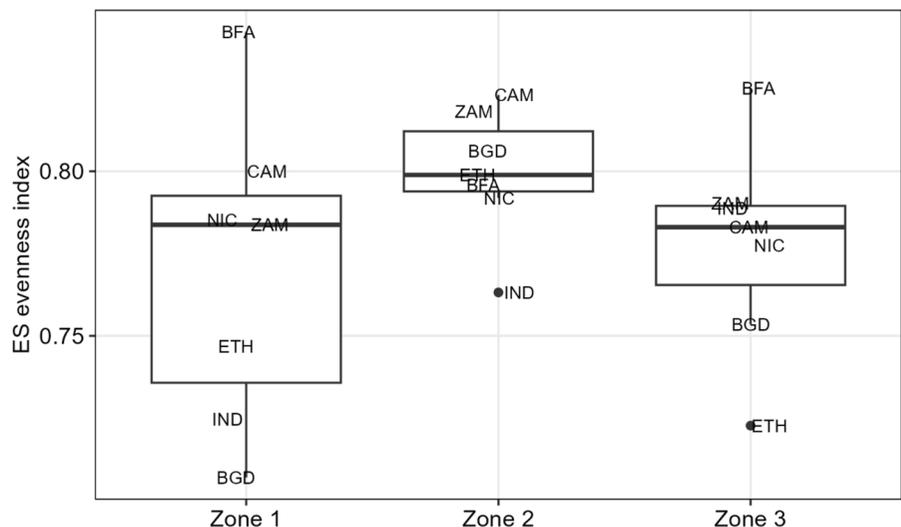
compared to the lower two ($P < 0.001$) across all countries (Fig. 4). No significant difference was found within the lower two wealth quintiles (between quintiles 1 and 2) and top two wealth quintiles (between quintiles 4 and 5). The analysis at the individual country level also showed a higher ES use by the top two wealth quintiles compared to the lower two. However, we observed country-specific variations in the use of ES in Cameroon, where the lower wealth quintile had the lowest use of ES ($P < 0.01$). In Indonesia, no significant difference was observed between different wealth quintiles.

Further analysis also shows no significant differences in ES use by functional groups across wealth categories. The evenness index of the specific ecosystem services within the functional groups showed a high abundance and equality in zone 2 compared to zones 1 and 3 (Fig. 5). However, no significant differences in the relative abundance of ES were observed between the three zones.

Synergies and trade-offs among groups of ES across the agricultural production zones

Our analysis of the interactions of ES shows their synergies or trade-offs across the agricultural production zones and wealth groups in each country (Fig. 6). The correlation analysis showed 61 significant (with Bonferroni corrected $P < 0.001$) pairs of ecosystem services interactions (of 153 possible) across zones. The significant pairs of ecosystem

Fig. 5 ES evenness shows the abundance or distribution of ES reported by households along gradient of increasing agricultural production across countries of Burkina Faso (BFA), Bangladesh (BGD), Cameroon (CAM), Ethiopia (ETH), Indonesia (IND), Nicaragua (NIC) and Zambia (ZAM)



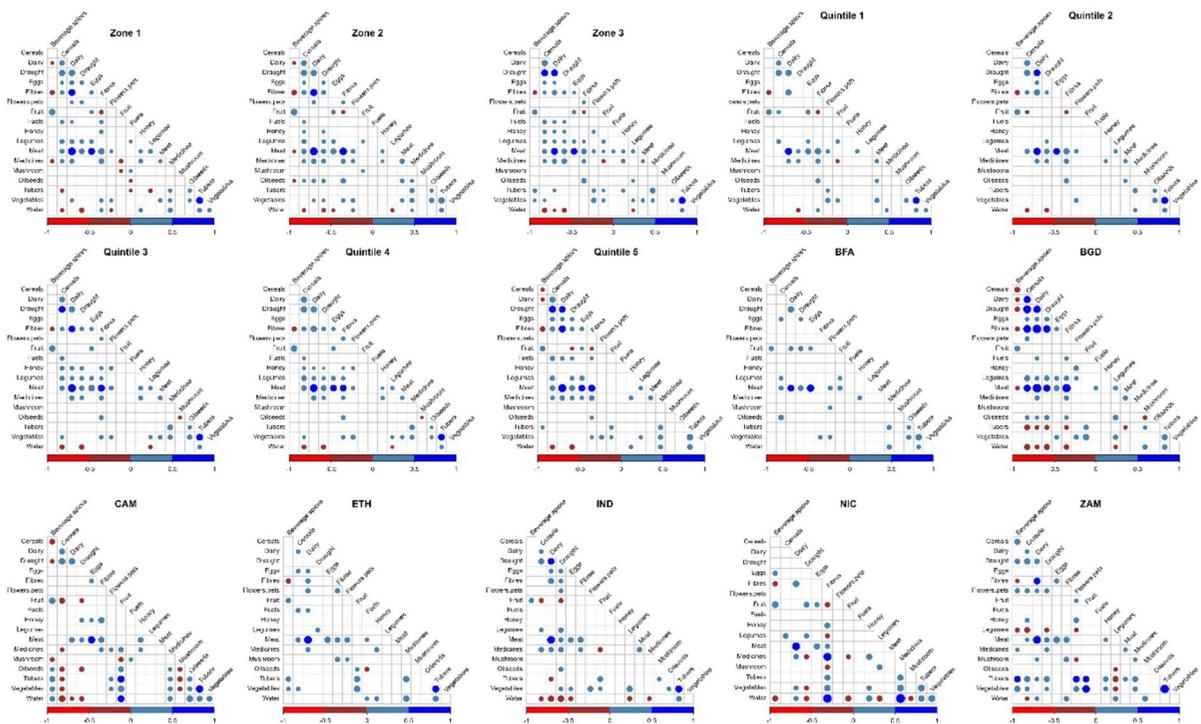


Fig. 6 Pairwise correlation coefficients between pairs of the functional groups of ES within each zone, wealth level and country. All the correlation coefficients of the pairs of ES are significant at $P < 0.001$. The size of the circles indicates the

services are shown in colour in Fig. 6. Most correlations were positive across each zone of the surveyed countries. In zone 3 and 2, 59 and 53 pairs of positive correlations (synergies) (out of total 66 and 62 pairs respectively) were recorded whereas 50 positively correlated pairs of ecosystem services functional groups in zone 1 (out of total 63). More negatively correlated (trade-offs) pairs of ecosystem services groups were found in zone 1 (13) than zone 2 (9 pairs) and 3 (7 pairs). Both a high number (12) and strength of correlations (> 0.50) among pairs for meat, dairy, eggs, vegetables, tubers, cereals, draught and fibres functional groups was observed. Further analysis shows that wealthier households (quintiles 3–5) experience more synergies (45–46 ES pairs) than poorer households (quintiles 1 and 2) which saw 30–32 pairs of synergies. At the country level, a higher number of synergistic ES pairs were found in the households of Zambia (47) and Bangladesh (45), whereas Burkina Faso (26) was the lowest.

correlation coefficients (blue for positive and red for negatively correlated pairs). Countries refer to Burkina Faso (BFA), Bangladesh (BGD), Cameroon (CAM), Ethiopia (ETH), Indonesia (IND), Nicaragua (NIC) and Zambia (ZAM)

Discussion

Does ES use by household differ with increasing agricultural production?

The first finding was a pattern of decreasing richness of provisioning ES reported by households in tandem with increasing agricultural production in all but one country. This pattern concurs with other studies linking changes in tropical land use towards more intensive agricultural production associated with the simplification of diets (Ickowitz et al. 2014; Ritzema et al. 2019; Gergel et al. 2020). The higher numbers of ES used by people in the low and moderate production zone (zone 1 and 2) suggest resources from a combination of forest and agricultural land provide a greater variety of wild foods and fuels, cultivated crops, and livestock. In contrast, the declining numbers of ES in the high production zone (zone 3) linked to households relying more on simplified land uses composed of monocultures along with

markets for cash crops for meeting dietary needs was in agreement with previous studies (Waha et al. 2018; Ahammad et al. 2021). Intensive land use may drive increased yields and market integration may provide an opportunity for improved diets (as reported elsewhere Ickowitz et al. 2019; Ogotu et al. 2020). However, household ES richness (for provisioning ES) in high production zones remains low due to the lower diversity of crops on farms, and lower availability of forest and livestock products, or alternatives to these products. The quantity of provisioning ES used by local households and more distant consumers may be higher in zone 3 than in zones 1 and 2. The nuances of provisioning ES observed across zones of agricultural production suggest failing to account for those services—beyond just cultivated fields—may have implications for household dietary diversity, nutrition, health and overall well-being.

The second finding that emerged from our study was that people located in zones with lower agricultural production used more diverse ES (functional groups), indicating that options for substitution of ecosystem services to meet food, fuel and economic needs are more widely available when agricultural production is low. Forests (i.e., old growth forests), secondary forests, fallow land and seasonal agricultural crop lands provide diverse food sources within low production zone, which declines with intensive and monoculture agriculture land use systems (Gray et al. 2015; Mathys et al. 2023). Our finding matters because the greater the diversity of food items or food groups consumed in adequate quantity, the better the nutritional quality of the diet, the more positive the impact on health and well-being (Kennedy et al. 2007; Arimond et al. 2010). The declining richness of functional groups of ecosystem services across agricultural production zones indicates that households have fewer options when/if their food system sustains a shock (Hicks and Cinner 2014). Interestingly minimal difference of ES groups use between intermediate and high agricultural production zones indicate a further progression of intensive agriculture in a landscape scale across all countries. Furthermore, our finding suggests that specific social-ecological contexts and the level of intensification within a country may impact the ability of people to benefit from ecosystems.

The abundance of ES did not significantly differ along the gradient of increasing agricultural

production as people use relatively equal numbers of each functional group to meet their diverse provisioning needs. Higher abundance in ES use is only observed in the intermediate production zone compared to lower and higher production zones. Relatively better access to market and agroforestry systems with diverse land uses, including horticulture, positively mediates the abundance of ecosystem services in the intermediate zone (Baudron et al. 2019; Ahammad et al. 2021; Castle et al. 2021). This abundance also means people have relatively more options for maintaining these functional groups, contributing towards their ability to maintain stable access in the face of social, economic and ecological stressors. Although our findings draw upon pooled data across countries, specific social and environmental stressors might uniquely affect the stability of food systems within a country or a particular household. For instance, the expansion of farmlands for maize and wheat crop production in Ethiopia caused declining community-owned forests and grassland that food-insecure households used for various provisioning ES, including food, fuel wood and livestock grazing. In the case of Nicaragua, throughout the twentieth century, political instability, internal displacement induced migration, and natural disasters affected agriculture commodity production (cacao, cotton, banana) and possession of land ownership by small- and medium-sized landholders to sustain their food security. In Bangladesh, the transition from swidden farming to monoculture crop and tree-based land use has not increased food production but declined provisioning services, including water availability. Care should be taken to address these fine-scale vulnerabilities to economic and ecological stressors within specific agricultural contexts to inform locally appropriate policies.

ES use remains disproportional within households of different wealth conditions, reflecting the redistribution effects and inequitable use of resources due to agricultural changes. Higher levels of ES use within wealthy families indicate that the increased agriculture production has not benefited the lower socioeconomic groups. Although agricultural changes increased household economic capacity reported in other studies, we found overall declines in an equitable distribution of ES. Lower wealthy households have limited access to natural capital, particularly landholding, to receive direct economic

benefits through agroforests and commercial agriculture production. Our study warrants taking into account wealth distribution in households in land use planning given the agrarian change in a landscape. The land tenure and ownership arrangement must enable indigenous people and local community to realise the full potential of ecosystem benefits from the surrounding landscapes. Although no differences were found within diverse functional groups of ES across wealth classes, given the land use intensification, there are enough reasons for changing ES demand and desires by local people from land uses.

Do synergies and trade-offs among ES change across the gradients?

By exploring synergies and trade-offs in provisioning ES in different agricultural production zones, the third finding revealed that many households could benefit from co-production or positive relationships among ES, produced from their land or by gathering from local forests. Synergies were common among groups of ES across the three agricultural production zones. The familiar narrative within the ES literatures that provisioning ecosystem services are found in trade-off relationships with regulating services and more synergies between different regulating and between different cultural services (Howe et al. 2014; Lee and Lautenbach 2016). Our study, for the first time to our knowledge, explored the household-level synergies and trade-offs within the category of provisioning ES sourced from forest, agriculture, and livestock to determine if differences existed according to household wealth and along an agricultural intensification gradient. Various functional groups of provisioning ES were primarily positively correlated (as opposed to negatively correlated), suggesting many opportunities to foster synergies among ecosystem services at the household level. However, relationships among multiple ecosystem services vary spatially as some locations concentrate on concordant ecosystem services, whereas others may be prone to trade-offs (Qiu and Turner 2013). A deeper examination of the quantities of forest products (rather than the presence/absence shown here) is warranted to reveal deeper relationships among ecosystem services. The significantly higher synergies of ecosystem services in intermediate (moderate intensification zone 2) indicate people's greater reliance on forest

and agroforests in this zone than in the high production zone.

A significant number of pair-wise synergies was found between dairy, eggs, meat, draught power, fibres, medicine, vegetables, tubers, cereals and fruit in the intermediate and high intensified zones across the countries. More significant synergies between different ES functional groups were observed in the intermediate and high production zones, which are characterised by cash crops and better access to markets. These zone-specific synergistic patterns of ecosystem services reflect not only what people want to produce but also what they can gather from their surroundings, which is mediated by localised land composition, land tenure and markets (Dade et al. 2019; Qiu et al. 2021). Our findings concur with other studies that a complex combination of economic dependence, farming structures, transformed natural capital, and human inputs into intensive agricultural systems drive the supply and demand of ecosystem services (Briner et al. 2013; Yang et al. 2015). In addition, our study specifically explored how interactions among provisioning services, driven by different levels of market-oriented agricultural systems, influenced people's reliance on particular food groups and the substitutability of many other ecosystem services. Market-oriented agricultural systems affected the flow of other provisioning ecosystem services, including food and non-food commodities, across landscapes.

Finally, our study revealed both consistencies and differences in pair-wise interactions between ES along the gradients of increasing agricultural production. These patterns reflect the multifunctionality of agricultural landscapes and differing capacities to deliver various benefits for rural livelihoods. Although both the number of ES and broader functional groups declined in the high production zones, particular synergies within functional groups of ES were evident. This indicates the maintenance of some multifunctionality to support dietary diversity and well-being, despite increased agricultural production. This finding supports the notion that the dynamics of social-ecological systems are related to specific land-use contexts which influence the variety of agroecosystem management and corresponding outcomes for ecosystem services (Raudsepp-Hearne et al. 2010; Tamburini et al. 2020; Bennett et al. 2021; Meyfroidt et al. 2022). Our results thus argue agricultural production gradients as a critical basis for understanding

the patterns of ecosystem services interactions. Each agricultural context in the tropics, even within a same landscape of a country, is a complex social-ecological system with different levels of accessibility and availability of ecosystem services. As such, future research needs to examine whether the current flow of provisioning ES in a given land-use context is related to demand or production, whether these dynamics occur internally or externally, and at what scale these dynamics arise to understand the broad relationships with other ecosystem services in a landscape.

Studying agricultural intensification focusing on land use gradients is a new approach that provides an improved understanding of the fine-scale spatial variation in provisioning ES and a more nuanced perspective of their trade-offs and synergies with increased agricultural production. As many tropical landscapes worldwide are subject to increasing land use intensification, understanding ecosystem services along these gradients is critical to explaining the manifestation of the changes in a landscape given the specific land use contexts. The cross-site comparisons along a gradient of increasing agricultural production, such as ours, are valuable for inferring generalizable, broad-scale patterns of ES dependence by households which is not possible using individual case studies alone (Fagerholm et al. 2019). Our study specifically fills the gap of a systematic cross-site comparison which is rare in the methodologically disjointed field of ES research, and covers gradients of agricultural production with different levels of land use intensification and wealth.

Conclusion

Drawing a cross-country study, we examined patterns in household use of provisioning ES and their interactions in the face of increasing agricultural production. Our research findings indicate that the level of agricultural production in different land use gradients shapes the use of provisioning ecosystem services. Notably, the number of ES supporting livelihoods was greater in the subsistence agriculture zone and lower in the higher production zones of most countries. Furthermore, broader functional groups of provisioning ES declined in the higher production land use zones. This empirical evidence of our study points to a decline in the availability and diversity of

ecosystem services during the agrarian transition process, which could be similar to other tropical developing countries experiencing increased agricultural production. The observed pattern of more ES available within the wealthy households also reflects unequal access of relatively poorer households to ecosystem benefits leaving their livelihood insecure and leading to unsustainable use of natural resources.

Provisioning ES cover a broad spectrum of livelihood, food, nutrition, cultural and well-being contributions to Indigenous people and local communities globally, where our study has considered a few select categories of foods, fibre and energy-related ES. Future ES research can develop metrics for measuring the quantity of the different provisioning ES used (e.g., calories consumed). Further research should also assess social equity by looking at people's demand against the supply of ES to inform landscape planning.

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Author contributions SAT, SEG, DR and TS: conceived the study. TS and DR: designed sampling protocol. RA, FB, J-YDC, SF and DG: contributed data. RA, FB, SAT, JvV and SG: analysed data. RA and SAT: led the writing of the paper with significant contributions from FB, SEG, DR and TS, minor contributions from DG, SF, JvV. TS secured funding and managed the project in which this paper is a part.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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References

- Adams WM (2014) The value of valuing nature. *Science* 346:549–551.
- Adams H, Adger WN, Nicholls RJ (2018) Ecosystem services linked to livelihoods and well-being in the Ganges-Brahmaputra-Meghna Delta. In: Nicholls R, Hutton C, Adger W, Hanson S, Rahman M, Salehin M (eds) *Ecosystem services for well-being in deltas: integrated assessment for policy analysis*. Palgrave Macmillan, Cham, pp 29–47. https://doi.org/10.1007/978-3-319-71093-8_2
- Ahammad R, Stacey N (2016) Forest and agrarian change in the Chittagong Hill Tracts region of Bangladesh. In: Deakin EL, Kshatriya M, Sunderland TCH (eds) *Agrarian change in tropical landscapes*. Center for International Forestry Research, Bogor Barat, pp 190–233. <https://doi.org/10.17528/cifor/005867>
- Ahammad R, Stacey N, Sunderland TCH (2019a) Use and perceived importance of forest ecosystem services in rural livelihoods of Chittagong Hill Tracts, Bangladesh. *Ecosyst Serv* 35:87–98.
- Ahammad R, Stacey N, Eddy IM, Tomscha SA, Sunderland TCH (2019b) Recent trends of forest cover change and ecosystem services in eastern upland region of Bangladesh. *Sci Total Environ* 647:379–389.
- Ahammad R, Stacey N, Sunderland TCH (2021) Assessing land use changes and livelihood outcomes of rural people in the Chittagong Hill Tracts region, Bangladesh. *Land Degrad Dev* 32:3626–3638.
- Allen T, Prosperi P, Cogill B, Flichman G (2014) Agricultural biodiversity, social–ecological systems and sustainable diets. *Proceedings of the Nutrition Society* 73:498–508.
- Andersson KP, Smith SM, Alston LJ, Duchelle AE, Mwangi E, Larson AM, de Sassi C, Sills EO, Sunderlin WD, Wong GY (2018) Wealth and the distribution of benefits from tropical forests: Implications for REDD+. *Land Use Policy* 72:510–522.
- Arimond M, Wiesmann D, Becquey E, Carriquiry A, Daniels MC, Deitchler M, Fanou-Fogny N, Joseph ML, Kennedy G, Martin-Prevel Y, Torheim LE (2010) Simple food group diversity indicators predict micronutrient adequacy of women's diets in 5 diverse, resource-poor settings. *J Nutr* 140:2059S–2069S.
- Asaha S, Deakin L (2016) Land-use change and its influence on rural livelihoods, food security and biodiversity conservation in the Southwest Region of Cameroon. In: Deakin EL, Kshatriya M, Sunderland TCH (eds) *Agrarian change in tropical landscapes*. Center for International Forestry Research, Bogor Barat, pp 190–233. <https://doi.org/10.17528/cifor/005867>
- Ayala LM, van Eupen M, Zhang G, Pérez-Soba M, Martorano LG, Lisboa LS, Beltrao NE (2016) Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. *Sci Total Environ* 569:1159–1173.
- Bahar NH, Lo M, Sanjaya M, van Vianen J, Alexander P, Ickowitz A, Sunderland TCH (2020) Meeting the food security challenge for nine billion people in 2050: What impact on forests. *Glob Environ Chang* 62:102056.
- Balzan MV, Caruana J, Zammit A (2018) Assessing the capacity and flow of ecosystem services in multifunctional landscapes: evidence of a rural-urban gradient in a Mediterranean small island state. *Land Use Policy* 75:711–725.
- Bates D, Kliegl R, Vasishth S, Baayen H (2015) Parsimonious mixed models. arXiv preprint [arXiv:1506.04967](https://arxiv.org/pdf/1506.04967). <https://arxiv.org/pdf/1506.04967.pdf>
- Baudron F, Schultner J, Duriaux JY, Gergel SE, Sunderland TCH (2019) Agriculturally productive yet biodiverse: human benefits and conservation values along a forest-agriculture gradient in Southern Ethiopia. *Landsc Ecol* 34:341–356.
- Baudron F, Govaerts B, Verhulst N, McDonald A, Gérard B (2021) Sparing or sharing land? views from agricultural scientists. *Biol Cons* 259:109167.
- Bennett EM, Baird J, Baulch H et al (2021) Ecosystem services and the resilience of agricultural landscapes. *Adv Ecol Res* 64:1–43.
- Berry ZC, Jones KW, Aguilar LRG et al (2020) Evaluating ecosystem service trade-offs along a land-use intensification gradient in central Veracruz. *Mexico Ecosystem Services* 45:101181.
- Briner S, Huber R, Bebi P, Elkin C, Schmatz DR, Grêt-Regamey A (2013) Trade-offs between ecosystem services in a mountain region. *Ecology and Society*. <http://www.jstor.org/stable/26269360>
- Broegaard RB, Rasmussen LV, Dawson N, Mertz O, Vongvisouk T, Grogan K (2017) Wild food collection and nutrition under commercial agriculture expansion in agriculture-forest landscapes. *Forest Policy Econ* 84:92–101.
- Castella JC, Lestrelin G, Hett C, Bourgoin J, Fitriana YR, Heinimann A, Pfund JL (2013) Effects of landscape segregation on livelihood vulnerability: Moving from extensive shifting cultivation to rotational agriculture and natural forests in northern Laos. *Hum Ecol* 41:63–76.
- Castle SE, Miller DC, Ordonez PJ, Baylis K, Hughes K (2021) The impacts of agroforestry interventions on agricultural productivity, ecosystem services, and human well-being in low-and middle-income countries: a systematic review. *Campbell Syst Rev* 17:1167.
- Clark NE, Lovell R, Wheeler BW, Higgins SL, Depledge MH, Norris K (2014) Biodiversity, cultural pathways, and human health: a framework. *Trends Ecol Evol* 29:198–204.

- Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, Oneill RV, Paruelo J, Raskin RG (1997) The value of the world's ecosystem services and natural capital. *Nature* 387:253–260
- Curtis PG, Slay CM, Harris NL, Tyukavina A, Hansen MC (2018) Classifying drivers of global forest loss. *Science* 361:1108–1111.
- Dade MC, Mitchell MG, McAlpine CA, Rhodes JR (2019) Assessing ecosystem service trade-offs and synergies: the need for a more mechanistic approach. *Ambio* 48(10):1116–1128.
- Daily GC (1997) *Nature's services: Societal dependence on natural ecosystems*. Island Press, Washington. <https://doi.org/10.12987/9780300188479-003>
- Daw TIM, Brown K, Rosendo S, Pomeroy R (2011) Applying the ecosystem services concept to poverty alleviation: the need to disaggregate human well-being. *Environ Conserv* 38:370–379
- Deakin EL, Kshatriya M, Sunderland TCH (2016) *Agrarian Change in tropical landscapes*. Centre for International Forestry Research, Bogor
- DeFries RS, Rudel T, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat Geosci* 3:178–181.
- DeFries R, Fanzo J, Remans R, Palm C, Wood S, Anderman TL (2015) Metrics for land- scarce agriculture: nutrient content must be better integrated into planning. *Science* 349:238–240.
- Dhyani S, Dhyani D (2016) Significance of provisioning ecosystem services from moist temperate forest ecosystems : lessons from upper Kedarnath. *Energy Ecol Environ* 1:109–121.
- Duriaux-Chavarria JY, Baudron F, Gergel SE, Yang KF, Eddy IM, Sunderland TCH (2021) More people, more trees: a reversal of deforestation trends in Southern Ethiopia. *Land Degrad Dev* 32:1440–1451.
- Fagerholm N, Torralba M, Moreno G, Girardello M, Herzog F, Aviron S, Burgess P, Crous-Duran J, Ferreiro-Domínguez N, Graves A, Hartel T (2019) Cross-site analysis of perceived ecosystem service benefits in multifunctional landscapes. *Glob Environ Change* 56:134–147.
- FAO (2010) *World Programme for the Census of Agriculture*. https://www.fao.org/fileadmin/templates/ess/documents/world_census_of_agriculture/appendix3_r7.pdf
- Fedele G, Donatti CI, Bornacelly I, Hole DG (2021) Nature-dependent people: Mapping human direct use of nature for basic needs across the tropics. *Glob Environ Chang* 71:102368.
- Ferreira RB, Parreira MR, Nabout JC (2021) The impact of global climate change on the number and replacement of provisioning ecosystem services of Brazilian Cerrado plants. *Environ Monit Assess* 193:731.
- Filmer D, Pritchett LH (2001) Estimating wealth effects without expenditure data—or tears: an application to educational enrollments in states of India. *Demography* 38:115–132.
- Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH (2005) Global consequences of land use. *Science* 309:570–574.
- Foli S, Abdoulaye R (2016) Drivers and outcomes of changing land use in parkland agroforestry systems of central Burkina Faso. In: Deakin EL, Kshatriya M, Sunderland TCH (eds) *Agrarian change in tropical landscapes*. Center for International Forestry Research, Bogor Barat, pp 190–233.
- Gergel SE, Powell B, Baudron F, Wood SL, Rhemtulla JM, Kennedy G, Rasmussen LV, Ickowitz A, Fagan ME, Smithwick EA, Ranieri J (2020) Conceptual links between landscape diversity and diet diversity: a roadmap for transdisciplinary research. *Bioscience* 70:563–575.
- Gibbs H, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc Natl Acad Sci* 107:16732–16737.
- Godfray H CJ, Garnett T (2014) Food security and sustainable intensification. *Phil Trans R Soc b: Biol Sci* 369:20120273.
- Godfray H CJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. *Science* 327:812–818.
- Gray CL, Bozigar M, Bilsborrow RE (2015) Declining use of wild resources by indigenous peoples of the Ecuadorian Amazon. *Biol Cons* 182:270–277.
- Gumbo DJ, Mumba KY, Kaliwile MM, Moombe KB, Mfuni TI (2016) Agrarian changes in the Nyimba District of Zambia. In: Deakin EL, Kshatriya M, Sunderland TCH (eds) *Agrarian change in tropical landscapes*. Center for International Forestry Research, Bogor Barat, pp 190–233.
- Hicks CC, Cinner JE (2014) Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs. *Proc Natl Acad Sci* 111:17791–17796.
- Hjelm L, Mathiassen A, Miller D, Wadhwa A (2017) *VAM-Guidance paper: Creation of a wealth index*. World Food Programme. https://docs.wfp.org/api/documents/WFP-0000022418/download/?_ga=2.180819055.913872412.1694431659-555613628.1694431659
- HLPE (2017) *Sustainable forestry for food security and nutrition*. A report by the high level panel of experts on food security and nutrition of the Committee on World Food Security, Rome. https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-11_EN.pdf
- Howe C, Suich H, Vira B, Mace GM (2014) Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Glob Environ Change* 28:263–275.
- Ickowitz A, Powell B, Salim MA, Sunderland TCH (2014) Dietary quality and tree cover in Africa. *Glob Environ Change* 24:287–294.
- Ickowitz A, Rowland D, Powell B, Salim MA, Sunderland TCH (2016) Forests, trees, and micronutrient-rich food consumption in Indonesia. *PLoS ONE* 11:0154139.
- Ickowitz A, Powell B, Rowland D, Jones A, Sunderland TCH (2019) Agricultural intensification, dietary diversity, and markets in the global food security narrative. *Glob Food Sec* 20:9–16.

- Ickowitz A, McMullin S, Rosenstock T, Dawson I, Rowland D, Powell B, Mausch K, Djoudi H, Sunderland TCH, Nurhasan M, Novak A (2022) Transforming food systems with trees and forests. *Lancet Planetary Health* 6:632–639.
- Johns T, Eyzaguirre PB (2006) Linking biodiversity, diet and health in policy and practice. *Proc Nutr Soc* 65:182–189.
- Karimi A, Raymond CM (2022) Assessing the diversity and evenness of ecosystem services as perceived by residents using participatory mapping. *Appl Geogr* 138:102624.
- Kennedy GL, Pedro MR, Seghieri C, Nantel G, Brouwer I (2007) Dietary diversity score is a useful indicator of micronutrient intake in non-breast-feeding. *J Nutr* 137(2):472–477.
- Khoury CK, Bjorkman AD, Dempewolf H, Ramirez-Villegas J, Guarino L, Jarvis A, Rieseberg LH, Struik PC (2014) Increasing homogeneity in global food supplies and the implications for food security. *Proc Natl Acad Sci* 111:4001–4006.
- Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci* 108:3465–3472.
- Lau JD, Hicks CC, Gurney GG, Cinner JE (2018) Disaggregating ecosystem service values and priorities by wealth, age, and education. *Ecosyst Serv* 29:91–98.
- Laurance WF, Sayer J, Cassman KG (2014) Agricultural expansion and its impacts on tropical nature. *Trends Ecol Evol* 29:107–116.
- Lee H, Lautenbach S (2016) A quantitative review of relationships between ecosystem services. *Ecol Ind* 66:340–351.
- Leonald L, Rowland D (2016) Drivers and effects of agrarian change in Kapuas Hulu Regency, West Kalimantan, Indonesia. In: Deakin EL, Kshatriya M, Sunderland TCH (eds) *Agrarian change in tropical landscapes*. Center for International Forestry Research, Bogor Barat, pp 190–233. <https://doi.org/10.17528/cifor/005867>
- MA (2005) *Ecosystems and human well-being: synthesis*. Island Press, Washington, DC. <https://www.millenniumassessment.org/documents/document.356.aspx.pdf>
- Mastrangelo ME, Weyland F, Villarino SH, Barral MP, Nahuelhual L, Laterra P (2014) Concepts and methods for landscape multifunctionality and a unifying framework based on ecosystem services. *Landsc Ecol* 29:345–358.
- Mathys AS, van Vianen J, Rowland D, Narulita S, Palomo I, Pascual U, Sutherland IJ, Ahammad R, Sunderland TCH (2023) Participatory mapping of ecosystem services across a gradient of agricultural intensification in West Kalimantan. *Indonesia Ecosyst People* 19:2174685.
- Meyfroidt P, de Bremond A, Ryan CM et al (2022) Ten facts about land systems for sustainability. *Proc Natl Acad Sci* 119:2109217118.
- Mouchet MA, Lamarque P, Martín-López B, Crouzat E, Gos P, Byczek C, Lavorel S (2014) An interdisciplinary methodological guide for quantifying associations between ecosystem services. *Global Environ Change* 28:298–308.
- Nakagawa S, Schielzeth H (2013) A general and simple method for obtaining R² from generalized linear mixed-effects models. *Methods Ecol Evol* 4:133–142.
- Nelson E, Mendoza G, Regetz J, Polasky S, Tallis H, Cameron D, Chan KM, Daily GC, Goldstein J, Kareiva PM, Lonsdorf E (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front Ecol Environ* 7:4–11
- Ogutu SO, Gödecke T, Qaim M (2020) Agricultural commercialisation and nutrition in smallholder farm households. *J Agric Econ* 71:534–555.
- Pascual U, Muradian R, Brander L et al (2010) The economics of valuing ecosystem services and biodiversity. *The Economics of Ecosystems and Biodiversity (TEEB)*. <https://www.teebweb.org/wp-content/uploads/2013/04/D0-Chapter-5-The-economics-of-valuing-ecosystem-services-and-biodiversity.pdf>. Accessed 03 Mar 2023
- Paumgarten F, Shackleton CM (2009) Wealth differentiation in household use and trade in non-timber forest products in South Africa. *Ecol Econ* 68:2950–2959.
- Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. *Philos Trans R Soc B* 365:2959–2971.
- Qiu J, Turner MG (2013) Spatial interactions among ecosystem services in an urbanizing agricultural watershed. *Proc Natl Acad Sci* 110:12149–12154.
- Qiu J, Queiroz C, Bennett EM, Cord AF, Crouzat E, Lavorel S, Maes J, Meacham M, Norström AV, Peterson GD, Seppelt R (2021) Land-use intensity mediates ecosystem service tradeoffs across regional social-ecological systems. *Ecosyst People* 17:264–278.
- Rasmussen LV, Coolsaet B, Martin A, Mertz O, Pascual U, Corbera E, Dawson N, Fisher JA, Franks P, Ryan CM (2018) Social-ecological outcomes of agricultural intensification. *Nat Sustain* 1:275–282.
- Rasolofson RA, Hanauer MM, Pappinen A, Fisher B, Ricketts TH (2018) Impacts of forests on children's diet in rural areas across 27 developing countries. *Sci Adv* 4:2853.
- Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc Natl Acad Sci* 107:5242–5247.
- Reed J, van Vianen J, Foli S, Clendenning J, Yang K, Macdonald M, Petrokofsky G, Padoch C, Sunderland TCH (2017) *Forest Policy and Economics Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics*. *Forest Policy Econ* 84:62–71.
- Ritzema RS, Douxchamps S, Fraval S, Bolliger A, Hok L, Phengsavanh P, Long CTM, Hammond J, van Wijk MT (2019) Household-level drivers of dietary diversity in transitioning agricultural systems: evidence from the Greater Mekong Subregion. *Agric Syst* 176:102657.
- Rutstein SO (2008) The DHS wealth index: approaches for rural and urban areas. Macro International Incorporated. Calverton. <https://dhsprogram.com/pubs/pdf/wp60/wp60.pdf>
- Smits J, Steendijk R (2015) The international wealth index (IWI). *Soc Indic Res* 122:65–85.
- Sunderland TCH, Abdoulaye R, Ahammad R, Asaha S, Baudron F, Deakin E, Duriaux JY, Eddy I, Foli S, Gumbo D, Khatun K, Kondwani M, Kshatriya M, Leonald L, Rowland D, Stacey N, Tomscha S, Yang K, Gergel S, van Vianen J (2017) A methodological approach for assessing cross-site landscape change: understanding socio-ecological systems. *Forest Policy Econ* 84:83–91.
- Sutton PC, Costanza R (2002) Global estimates of market and non-market values derived from nighttime satellite

- imagery, land cover, and ecosystem service valuation. *Ecol Econ* 41:509–527.
- Tadesse G, Zavaleta E, Shennan C, FitzSimmons M (2014) Prospects for forest-based ecosystem services in forest-coffee mosaics as forest loss continues in southwestern Ethiopia. *Appl Geogr* 50:144–151.
- Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MG, Liebman M, Hallin S (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv* 6:1715.
- Tilman D (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. *Proc Natl Acad Sci* 96:5995–6000.
- Vyas S, Kumaranayake L (2006) Constructing socio-economic status indices: how to use principal components analysis. *Health Policy Plan* 21:459–468.
- Waha K, Van Wijk MT, Fritz S, See L, Thornton PK, Wichern J, Herrero M (2018) Agricultural diversification as an important strategy for achieving food security in Africa. *Glob Change Biol* 24(8):3390–3400.
- Weerasekara PC, Withanachchi CR, Ginigaddara GAS, Ploeger A (2020) Understanding dietary diversity, dietary practices and changes in food patterns in marginalised societies in Sri Lanka. *Foods* 9:1659.
- Yang G, Ge Y, Xue H, Yang W, Shi Y, Peng C, Du Y, Fan X, Ren Y, Chang J (2015) Using ecosystem service bundles to detect trade-offs and synergies across urban–rural complexes. *Landsc Urban Plan* 136:110–121.

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