Carbon Footprints

Perspective

Open Access

Check for updates

Carbon footprints, informed consumer decisions and shifts towards responsible agriculture, forestry, and other land uses?

Meine van Noordwijk[1,2,3], Thuy T. Pham[1], Beria Leimona[1], Lalisa A Duguma[1], Himlal Baral[1,4], Nikhmatul Khasanah[1], Sonya Dewi[1], Peter A. Minang[1]

[1]Centre for International Forestry Research and World Agroforestry (CIFOR-ICRAF), Bogor 16115, Indonesia.
[2]Department of Plant Production Systems, Wageningen University and Research, Wageningen PB 6708, the Netherlands.
[3]Agroforestry Research Group, Brawijaya University, Malang 65145, Indonesia.
[4]School of Ecosystem and Forest Sciences, University of Melbourne, Parkville VIC 3010, Australia.

Correspondence to: Dr. Meine van Noordwijk, Department of Plant Sciences, Wageningen University and Research, Droevendaalsesteeg 4, Wageningen, PB 6708, The Netherlands. E-mail: m.vannoordwijk@cgiar.org

How to cite this article: van Noordwijk M, Pham TT, Leimona B, Duguma LA, Baral H, Khasanah N, Dewi S, Minang PA. Carbon footprints, informed consumer decisions and shifts towards responsible agriculture, forestry, and other land uses? *Carbon Footprints* 2022;1:4. https://dx.doi.org/10.20517/cf.2022.02

Received: 15 Feb 2022 **First Decision:** 21 Mar 2022 **Revised:** 27 Mar 2022 **Accepted:** 11 Apr 2022 **Published:** 17 Apr 2022

Academic Editor: P. K. Ramachandran Nair **Copy Editor:** Jia-Xin Zhang **Production Editor:** Jia-Xin Zhang

Abstract

The urgent global reduction of greenhouse gas emissions depends on political commitments to common but differentiated responsibility. Carbon footprints as a metric of attributable emissions reflect individually determined contributions within, and aggregated national contributions between, countries. Footprints per unit product (e.g., of food, feed, fuel, or fiber) require a lifecycle analysis and support individual decisions on consumption and lifestyles. This perspective presents a framework for analysis that connects the various operationalizations and their use in informing consumer and policy decisions. Footprints show geographical variation and are changing as part of political-economic and social-ecological systems. Articulation of footprints may trigger further change. Carbon footprints partially correlate with water and biodiversity footprints as related ecological footprint concepts. The multifunctionality of land use, as a solution pathway, can be reflected in aggregated footprint metrics. Credible footprint metrics can contribute to change but only if political commitments and social-cultural values and responsibilities align.

Keywords: Agriculture, forestry and other land uses (AFOLU), ecological footprint, indirect carbon emissions, land use, lifecycle analysis, nationally determined contributions (NDC), theories of change, theories of place

INTRODUCTION

Historically, the concept of carbon footprint emerged as part of a more comprehensive "ecological footprint" concept[1-3], which is the area "of productive land and water ecosystems required to produce the resources that a population consumes and to assimilate the wastes that the population produces, wherever on Earth that land and water may be located" as its primary metric [Figure 1]. The choice of "area" as a metric, linked to the footprint metaphor, helped to popularize the concept, while it could be converted to a temporal equivalent in calculating the annual "overshoot day", where consumption starts to exceed sustainable supply[4].

Fifty years after Meadows *et al.*[5] (1972), the urgency of climate action has been widely accepted, but the pathways to deal with it remain contested. Nation-states, a globalized corporate sector, and global citizens are important parts of the problem and have to be part of the solution. The latest synthesis by the Intergovernmental Panel on Climate Change (IPCC) of the human influence on C cycles shows[6] that the increased concentration of greenhouse gasses (GHG) has already reached a global warming effect of 1.5 °C. However, emission of "cooling gasses" such as sulfur dioxide is neutralizing part of the warming, defining an inconvenient truth on a tradeoff between air pollution control for local health benefits and global climate change control. Total anthropogenic GHG emissions can be attributed to the country where they occurred, the economic activity and sectors that caused them, the products generated, or the consumers whose needs were satisfied. However, the likelihood of gaps between different accounting approaches (and/or for double-counting) is considerable when attributions to countries, sectors, products and citizens are intermingled. However, that is the current reality with multiple footprint concepts.

As nation-states have collectively failed in the first thirty years after the UN Framework Convention for Combatting Climate Change (UNFCCC) to resolve the necessary energy transition and address the drivers of deforestation and degradation in a timely fashion, citizens' concern over the urgency of the issues kept increasing. Pathways towards solutions have a territorial dimension [mostly based on nation-states and their nationally determined contributions (NDC)[7]] and a supply/demand, market-based one that depends on actors along supply and value chains as well as consumers and voluntary, individually determined contributions to emission control. Both the territorial and market-based pathways are needed to decouple economic success, resource use, and GHG emissions[8] and jointly achieve the Sustainable Development Goals (SDG).

An alternative arena for state-based action arose in the personal responsibility for the "footprint" consequences of consumption and lifestyle choices. Such initiatives started especially in the Global North, driven by young people, but were followed up elsewhere[9,10]. The (threats of) boycotts of products, such as palm oil, which were singled out in public communication, led to responses by part of the global corporate sector, keen to protect their branding and public image. The result has been an avalanche of declarations, commitments, and stated ambition to become deforestation-free, carbon-neutral, carbon-negative, *etc.*[11]. Nation-states, a globalized corporate sector, and global citizens interact in the "governance" and "consumption-based" interfaces [Table 1] that shape current actions.

Table 1. Three ways global anthropogenic emissions can be accounted for and governed

	Nation-states	Private (corporate) sector	Consumers, citizens
Accounting target	Net anthropogenic emissions within national boundaries; pledged and supported NDC	Emission intensity (attributable emissions per unit economic turnover)	Per capita emissions; Individual footprints (domestic + global)
Gaps	Accountability for EET, including imported biofuels; international waters; C sink saturation	Transnational corporations; sea and air transport; responsibility for "indirect land-use change" (ILUC)	Lifecycle accounting beyond consumable products, including "services", waste, and recycling
Interfaces	Governance: carbon markets created by tradeable emission rights for corporations; REDD+; carbon tax at international borders		Response to changing prices for goods and services
	Fear of loss of sovereignty, national standards to regain trust and maintain exports	Consumption-based: Consumer pressure to obtain "cheap but green" products; sector-level standards, commitments, certification	

NDC: Nationally determined contribution; EET: emissions embodied in trade: REDD+: Reducing Emissions from Deforestation and (Forest) Degradation.

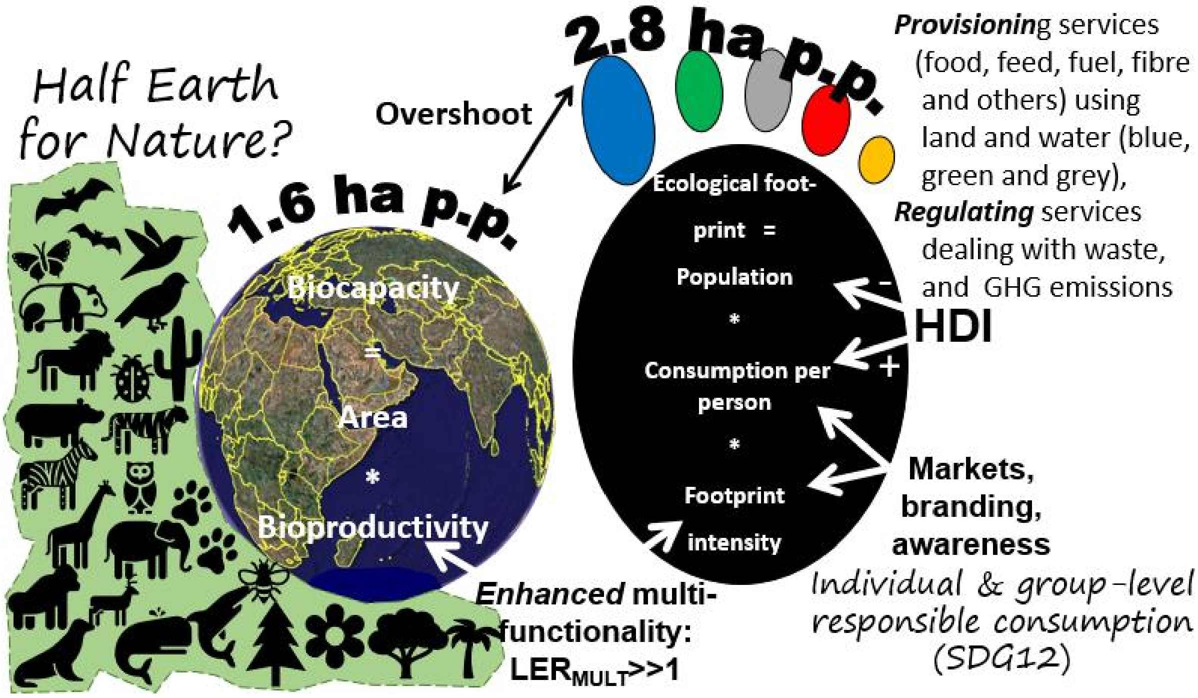

Figure 1. Visualizing the "footprint exceeding the planet" metaphor with global data for 2017. Available from: https://data.footprintnetwork.org/#/countryTrends?cn=5001&type=earth [Last accessed on 15 Apr 2022], and the leverage points of the Human Development Index (HDI), individual and group-level responsible consumption, and increased bioproductivity (evaluated at multifunctional level). The half-earth for nature debate[42] is not yet reflected in footprint calculations.

Where nation-states became the primary agents in UN-based discussions, the route to change via global citizens, consumer power, and a responsive corporate sector (that wants to be seen as responsible for their individually determined contributions) remains a separate track with challenging "market-based" interfaces with NDCs of the countries in which goods are produced, consumers reside, and/or companies have their legal basis.

Carbon footprints relate GHG emissions to decisions made. Wiedmann and Minx (2008)[12] provided an often-cited definition of "carbon footprint" in a context of ecological economics as "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an ***activity*** or is accumulated over the life stages of a ***product***. This includes activities of individuals, populations, governments, companies, organizations, processes, industry sectors, etc. Products include goods and services. In any case, all direct (on-site, internal) and indirect emissions (off-site, external, embodied, upstream, downstream) need to be taken into account." Subsequently, the carbon-equivalence of other GHGs has been included, as indicated in the instruction to authors of this journal: "The term carbon footprint refers to the emissions of all greenhouse gases including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons, and is expressed as the amount (tons) of CO_2 produced during a given period."[13].

The quantification of these various footsteps can be derived from a common basis of accounting for land use [Figure 2]. It all starts from a land cover classification that allows all land units to be mapped without double-counting or gaps so that area fraction, time-averaged (system level) C stocks, and the emissions of N_2O and CH_4 can be measured. This is the basis of national GHG accounting of the land-use sectors, with input production and transport accounted elsewhere. However, land use yields marketable commodities, and these can be the basis of product-based accounting when other parts of their lifecycle are added and summed for the footprint of food production as part of the global food system. When consumption is differentiated by societal groups or individuals, further footprint calculations become possible.

Four carbon footprint concepts play a role in discussions on both supply and demand-based pathways [Figure 2]: (1) historical and current per capita emissions as an argument of fairness in NDCs declarations; (2) emissions per unit economic activity as the economic footprint for the efficiency argument in NDC declarations; (3) product-level footprints derived from a lifecycle analysis (e.g., for food, feed, fuel, or fiber); and (4) consumption-level, individual footprints, differentiated by wealth and lifestyle. The latter types of carbon footprints supposedly inform consumer decisions and support shifts towards development strategies with low emissions of carbon and other greenhouse gasses. Footprints can function as boundary objects as they are entities that enhance the capacity of an idea, theory, or practice to translate across culturally defined boundaries, for example, between communities of knowledge or practice[14]. Their derivation and use are a form of boundary work[15] and have to meet the quality criteria of credibility, salience, and legitimacy.

In reviewing evidence for such a theory of change, we focus on three questions:

Q1. How are the operational definitions of various types of carbon footprints related to consistent accounting for GHG emissions?

Q2. How are footprint concepts used as boundary objects in public and private decision-making?

Q3. How might footprint concepts be improved?

For Q1, we provide backgrounds on human impacts on the global C cycle, discuss ecological footprints as an umbrella concept, and contrast footprint concepts 1-4 as part of governance- and business-based climate solutions. For Q2, we introduce four levels of leverage on complex, adaptive social-ecological systems, discuss theories of place and change across scales, and review theories of (induced) change concerning carbon footprints. For Q3, we summarize the findings on the first two questions and discuss ways forward.

Human impacts on the global C cycle

The chain of land users/producers, processors/transporters, and consumers has become increasingly global in its operational dynamics, with fossil-based energy sources interacting with and potentially substituted by

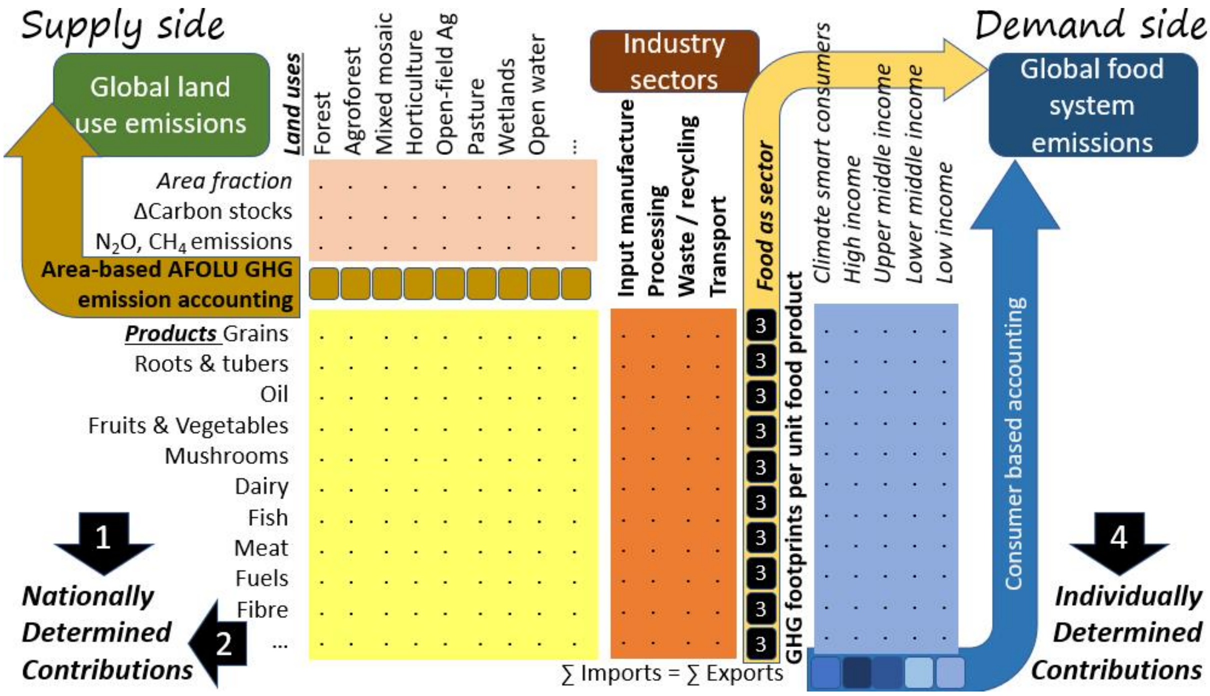

Figure 2. Nationally and individually determined contributions to global emission reduction based on the relationship between AFOLU land use (agriculture, forestry, and other land uses), the production of tradable commodities that through lifecycle analysis leads to product level footprints, and potentially informed consumer decisions. Four uses of footprint metrics are discussed in the text (modified from Ref.[27]).

land-based emissions [Figure 3]. Fossil fuels and land-based emissions have an increasing impact on atmospheric GHG concentrations as terrestrial and oceanic sinks are becoming saturated and risk becoming net emitters in a changing climate[16,17].

The global carbon budget can be described as having five major components, each with uncertainties but with internally consistent estimates[18]: (1) fossil CO_2 emissions (E_{FOS} 9.4 ± 0.5 GtC year^{-1}; based on energy statistics and cement production data); (2) emissions from land use and land-use change (E_{LUC} 1.6 ± 0.7 GtC year^{-1}; mainly deforestation, based on land use and land-use change data and bookkeeping models); (3) atmospheric CO_2 concentrations and its growth rate (G_{ATM} 5.1 ± 0.02 GtC year^{-1}, measured directly and computed from the annual changes in concentration); (4) the ocean CO_2 sink (S_{OCEAN} 2.5 ± 0.6 GtC year^{-1}); and (5) the terrestrial CO_2 sink (S_{LAND} 3.4 ± 0.9 GtC year^{-1}; estimated with global process models constrained by observations). The sum of the first two approximately equals that of the latter three ($E_{FOS} + E_{LUC} = G_{ATM} + S_{OCEAN} + S_{LAND}$). Footprints refer to the first two ($E_{FOS} + E_{LUC}$), taking the latter two ($S_{OCEAN} + S_{LAND}$) for granted, but both sinks are at risk. Technically, the rules for national reporting of GHG emissions have separate sections for croplands, grasslands, forestry, and wetlands, but all are based on accounting for changes in C stocks and recurrent emissions of CH_4 and N_2O and are mutually consistent[19]. However, the accounting is land-based and does not include industrial production of inputs such as fertilizer, or subsequent transport and processing (that are handled in separate chapters of the IPCC national accounting rules).

Annex I countries (also known as the Global North) could thus far meet their international obligations by outsourcing emission-intensive heavy industry to non-Annex I countries[20] and protecting their domestic forests while increasing their external footprint for agricultural and forestry products. Meyfroidt *et al.*[21] (2010) estimated a 50% area substitution from global trade statistics. Area footprints are translated to carbon

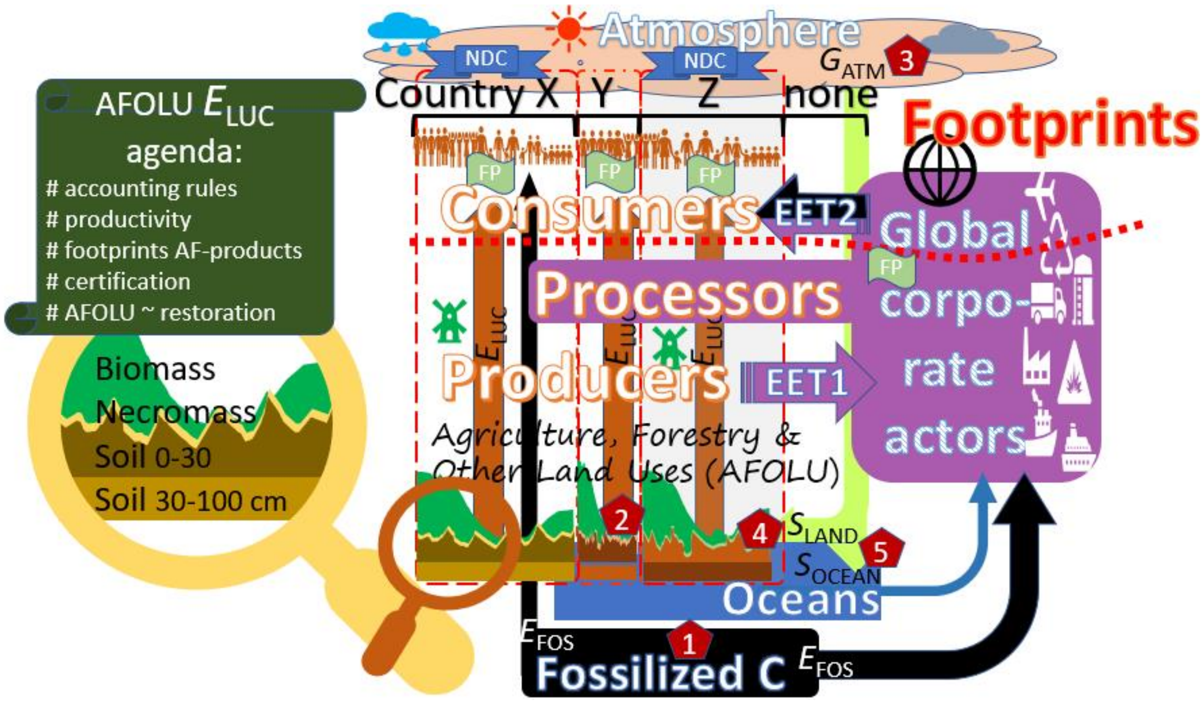

Figure 3. Overview of the cross-scale relations between local C stocks and GHG emissions and global climate change, with a nation-state-based relationship between land use and consumers and one in which global trade and global corporate actors play major roles. Global carbon budgets consider emissions from fossil sources (E_{FOS}) and land use (E_{LUC}), increases in atmospheric concentration (G_{ATM}), and the sink strength of oceans (S_{OCEAN}) and terrestrial systems (S_{LAND}). GHG: Greenhouse gasses.

footprint in the emissions embodied in trade (EET) literature[22-24], but may have further consequences in terms of biodiversity, water, pollution, or social impacts[25,26]. Country-level responsibility for and crediting of terrestrial (let alone oceanic) sinks remain an unresolved issue in the UNFCCC arena and are not addressed in current footprint definitions[27,28]. The sum of current NDC declarations still falls short of the globally accepted UNFCCC goals, even if there would not be an NDC implementation gap.

Footprints as part of governance- and business-based climate solutions

The corporate sector tries to build trust in its "brands" through its public commitments to social and environmental impacts. Without standardized reporting requirements that are compatible with national GHG accounting, however, the necessary public pressure to follow through on commitments is hampered. While well-intentioned global citizens try to minimize their "footprints", without clarity on how this contributes to NDCs, there is a risk of multiple claims of credits and a lack of synergy between governance- and business-based climate solutions. Behavioral change in response to consumption options can contribute to climate change mitigation[29], as the action may have to start at home[30], or in choices of how to travel away from and back to home. One of the accountability gaps is in the aviation industry. The global scale, distribution, and growth of aviation have implications for climate change[31]; these have been kept outside the reach of national accounting and policy responses so far but are on the radar screen of those wanting to express personal responsibility. The degree to which climate policies can effectively target household consumption and behavioral decisions is probably key to low-carbon futures. Footprints can help in the process as a relevant metric, with adequate attention to standards, data quality, and consistency. Standardization of footprint calculations for businesses and products has been achieved (ISO 2018a, b, ISO 2019), with specific challenges for the footprint of recycled products[32].

Current experience with demand-side solutions for climate mitigation is that the bottom-up drivers of household energy behavior change in ways that depend on the national context[33]. The distribution of household carbon footprints is largely unequal within and across countries in Europe[34]. Inequality is even larger globally as carbon footprints relate to socially desirable outcomes such as income, equality, education, nutrition, sanitation, employment, and adequate living conditions - the totality of the SDG agenda 2030[35-37]. Pathways between metrics such as carbon footprints and SDG attainment will need to be better understood.

Ecological footprints as an umbrella concept

Despite its "rhetorical appeal", scientific critiques and methodological weaknesses were seen as the demise of the ecological footprint as a basis for public policy processes[3]. This history may be repeating itself in the next reincarnation of multidimensional "environmental space" as the planetary boundary concept of Rockström *et al.*[38] (2009) and its safe operating space for humanity[39].

The overshoot of the human footprint over the global biocapacity [Figure 1] suggests three types of leverage points to reconcile supply and demand[36]:

A. More efficient (less resource-dependent) ways to achieve well-being for a growing population (along with progress to self-regulate human population size by supporting gender-balanced education;

B. Enhanced multifunctionality of land use (technically, the land equivalent ratio for multifunctionality (LER_{MULT}) is substantially above 1[36,40]).

C. Responsible consumption by well-informed and aware consumers, reliable footprint information, along with a continued increase in Human Development Index[41].

The footprint metaphor of current human impacts exceeding the carrying (or bio-)capacity of the planet [Figure 3] does not yet include impacts on biodiversity, for which a claim of "Half Earth for Nature"[42,43] is currently negotiated as part of the post-2020 Convention on Biodiversity targets (possibly watered down to a 30% target, and strongly dependent on how nature is interpreted[44]).

As many land uses are "multifunctional" and contribute to multiple commodity flows, an attribution system is needed within each type of footprint considered, e.g., based on the LER_{MULT} metrics[36]. Land-use change is a multi-phased process. The sharing across commodity flows of responsibility for emissions (stock change) is not easy, as a typical sequence of logging for high-value timber, overlogging for pulp-and-paper industry, and conversion to oil palm (*Elaeis guineensis*), coffee (*Coffea arabica* and *C. canephora*), or cocoa (*Theobroma cacao*) production shows. An example with apparently "deforestation-free" conversion of swiddens that otherwise would have recovered as secondary forests to coffee gardens was described for Vietnam[45,46].

Sustainable intensification of agriculture has been recognized as one of the requirements for human prosperity and global sustainability[47], but how this relates to simultaneously closing existing yield and efficiency gaps in multifunctional land use and their GHG emissions per unit product remains contested. In minimizing the ecological footprint of food, both the environmental impacts and the volume of production over which the load is shared are relevant[48]. The environmental impacts depend on "efficiency gaps" (where more inputs are needed and hence GHG emissions are higher than strictly necessary) and "yield gaps" (where achieved yield levels are lower than potential). Quantitative analysis for specific commodities suggests that, indeed, an intermediate level of "intensification" can minimize footprints[49]: a comparison of closing yield gaps in oil palm by increased fertilizer use, with associated increased emissions of N_2O as a potent GHG, suggested that minimizing the carbon footprint by optimal fertilizer use depends on past land cover history[50]. The results demonstrate the relevance of variation of carbon footprints within a commodity such as palm oil can easily exceed differences between average footprints of different bioenergy crops. This variation was discussed as "management swing potential" by Davis *et al.*[51] (2013). The size of the management swing potential is an argument for differentiating footprints of alternate production streams rather than of products as such.

Among the various components of the ecological footprints, the water footprint[52] may well be most compelling as the combination of increased demand for reliable, clean water coincides with more variable climates in which both drought and floods are a risk, and a diminished capacity of landscapes to buffer water flows[53]. Water footprints normally include the use of "blue" water (surface or groundwater), direct use of rainfall buffered in soils "green" water, and a "grey" water component (how much clean water is needed to dilute pollution to acceptable standards). A recent proposal for alternative metrics suggests using the water use by natural vegetation as the point of reference, as both downwind rainfall and downstream river flow are likely adjusted to that level of water use, and both increased and decreased groundwater flows can induce problems[54].

The carbon footprint metaphor appeared at the turn of the millennium and spread quickly, initially as a carbon component of the ecological footprint[28,55]. The initial estimates of an area equivalence were abandoned for the current definition in emission units. The basic appeal was that the carbon footprint of nations could add a global, trade-linked analysis to existing national emission accounting[56]. An overview of carbon footprint analysis by Wang *et al.*[57] (2010) stated: "This report explores the apparent discrepancy between public and academic use of the term 'carbon footprint' and suggests a scientific definition based on commonly accepted accounting principles and modeling approaches. It addresses methodological questions such as system boundaries, completeness, comprehensiveness, units, and robustness of the indicator" and "Whatever method is used to calculate carbon footprints, it is important to avoid double-counting along supply chains or life cycles".

Four levels of leverage on complex, adaptive social-ecological systems

Interventions in complex adaptive systems, such as landscapes in which various social actors make a living interacting with global markets while influencing local soils, watershed-level streamflow, and global atmosphere and climate, can easily have unexpected results. As there are many aspects to consider across many contexts, the classification Meadows (1999)[58] developed based on her experience with global system models of ways to leverage complex adaptive systems can be used. Simplified, the classification groups parameters (parameters and data), feedbacks (relationships), institutions (rules of the game), and goals as having an increasingly transformative impact on a social-ecological system. Ostrom (1990)[59] distinguished between two broad categories of public decisions: constitutional and allocational ones. The first, politically, shapes institutions (or policy instruments), including those for "commons" and for defining boundary conditions to, and interacting with, private (and corporate) decisions. The second, economically, uses institutions to modify benefit distribution within existing mandates. Jointly, these processes and their outcomes define governability[60] as a balance between the ambitions of all stakeholders and what can be operationalized. In the process of decision making, the bounded rationality that behavioral economics established experimentally[61] can be reconciled with (and be labeled more positively) the sociality concept[62], emphasizing (reference) groups, rituals, affiliation, status, and power as aspects. The ecosystem services concept suggests a one-way flow of benefits that are instrumental in achieving human goals. It appeals to rationality as the basis for decision-making. It has been augmented by an interest in relational values of nature as a two-way process depending on and justifying investment, appealing to sociality as the basis for decision-making[63].

While footprints are defined as metrics, their relevance for decision-making depends on the feedback relationships that they help understand, the institutions that are using them in rules and incentives, and how they appeal to goals that they can help achieve. Footprints can represent instrumental values, but are also, in the metaphor used, relational and appealing to accountability.

In the four levels of the Meadows-based hierarchy (1999)[58] [Figure 4], the relationship between constitutional plus allocational decisions and the three categories of nature-specific values (instrumental, relational, and intrinsic) can be understood:

Parameters: Data, metrics, and expected (discounted) costs and benefits associated with quantified instrumental ecosystem services as value aspects interact with explicit, often binary decisions to accept or not accept proposed projects, investment in programs or contracts.

Feedbacks: Transactional values, open to bargaining, reduced risk of investment, potential social payoffs, reciprocity and status indicators interact with *efficiency*-oriented decisions on roles, cost and benefit allocation among multiple actors/stakeholders, and attention to implementation and transaction costs.

Institutions: Value aspects such as recognition, rules of the game, stewardship, eudaimonia (social well-being as a complement to individual hedonics[64,65]), group (club) membership, and avoiding conflict interact with constitutional ("*effectiveness*") decisions about rules of the game, boundaries to rights, in-group membership/exclusion and security (risk sharing).

Goals: "Invaluable", non-negotiable core values of respect, identity-related self-expression, ethics, and sovereignty/autonomy concepts, such as free and prior informed consent, interact with *equity* decisions on universal goals, ways to internalize externalities, intergenerational responsibility and ensure continuity.

Theories of place and change across scales

The urgently needed transformation towards sustainability that addresses current development deficits without trespassing planetary boundaries needs to combine climate change mitigation and adaptation. It has to reconcile the hierarchy of individuals nested in households nested in communities nested in sub-national jurisdictions nested in nation-states part of global humanity [the vertical axis in Figure 5], with the hierarchy of levels of "leverage" on complex, adaptive social-ecological systems based on Meadows (1999)[58]: data, feedbacks, institutions, and goals [the horizontal axis in Figure 5]. These latters are related to the "issue attention cycles" of policy change[63,66].

Footprints are in the "data" column in Figure 5 but can be expressed at national (including "average citizen of country X"), subnational emission intensity, community, or individual level. Footprints, or the activities used as the denominator, are part of feedbacks. They can become a target for roles and rules as far as they represent recognized goals - at the individual, national, or global scales.

The lower-left to upper-right diagonal in Figure 5 connects local action to global goals and vice versa [Figure 6A]. The cells above the diagonal imply that one first move up the hierarchy from individuals towards governance structures, before shifting from data to feedback processes, to institutions and goals; we tentatively describe this as the governance route. In its extreme form, it determines (in the ultimate top-

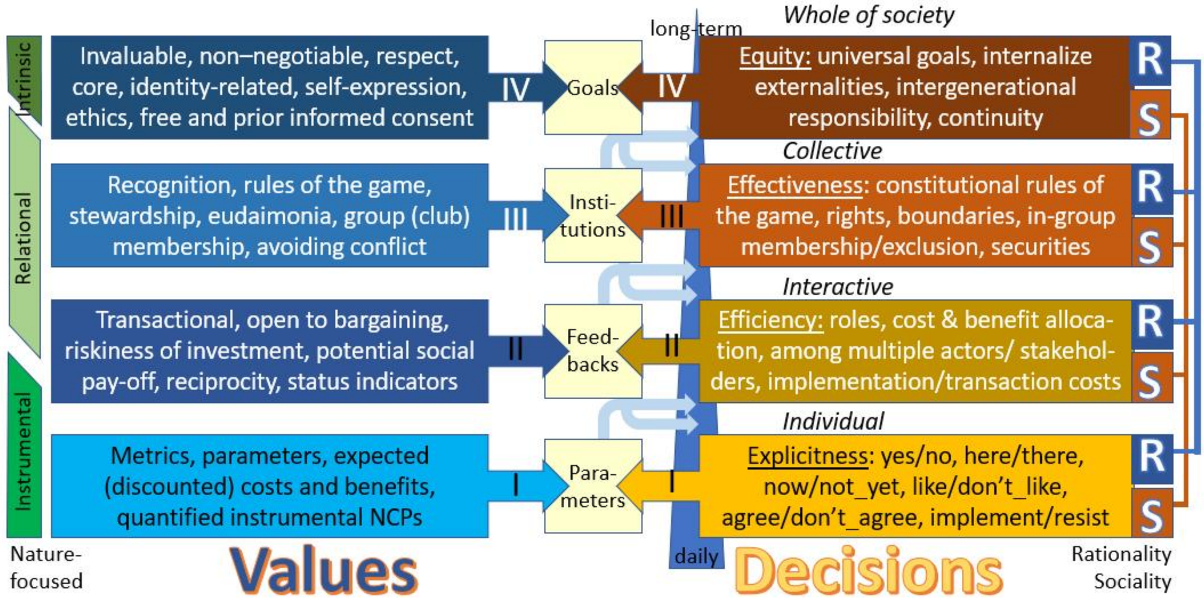

Figure 4. Values and decisions in their relation to parameters, feedbacks, institutions, and goals in the hierarchy of leverage points for complex, adaptive social-ecological systems[58].

	Data	Functional feedbacks	Rules&roles institutions	Goals
Global	SDG targets & indicators, IPCC, IPBES	Tipping points, Teleconnections, Scenario modeling	WTO, UNFCCC, CBD, REDD+, *0*-deforestation trade, C-tax	SDGs
National	National GHG communications, NDC reporting, Equity	Adjusted GDP, National Adaptation Plans, Disaster resp.	Parliaments, Laws, Ministries, Tax/subsidies, Invest	Constitution, Identity, Sovereignty, NDC, National development
Sub-national	Emission intensity CO_{2e}/GDP, OpCost, C-credits, Votes	Value addition, employment, equity, conflict, investment	Devolution, Land use plans & rights, Forest management, Permits	Green growth, Social-economic development, Land Use synergy
Community	Emission factors of land uses, Mimetrics, Risk estimates	Instrumental & relational value, Disaster vulnerability, Water	Co-management contracts, FPIC, Collective action, Commons	Resilient livelihoods, Respect, Eudaimonia, Spirituality
Individual	**Footprints,** Health, Awareness, Lifestyle choices, Wellbeing	Responsible consumption, certified products, coinvest	Human rights, education, resource use, tenure, jobs, health care, tax	Identity, Enterprise, Income, Voice, Basic needs, Security

Figure 5. Meadows-based hierarchy (data, feedbacks, institutions, and goals) across individual-to-global scales with examples of specific concerns in understanding and nudging societies (1999)[58]. CBD: Convention on Biological Diversity; FPIC: free and prior informed consent; GDP: gross domestic product; IPBES: Intergovernmental Science-Policy Panel on Biodiversity and Ecosystem Services; IPCC: Intergovernmental Panel on Climate Change; NDC: nationally determined contribution; OpCost: opportunity costs; REDD+: Reducing Emissions from Deforestation and (forest) Degradation; SDGs: Sustainable Development Goals; UNFCCC: UN Framework Convention on Combatting Climate Change; WTO: World Trade Organization.

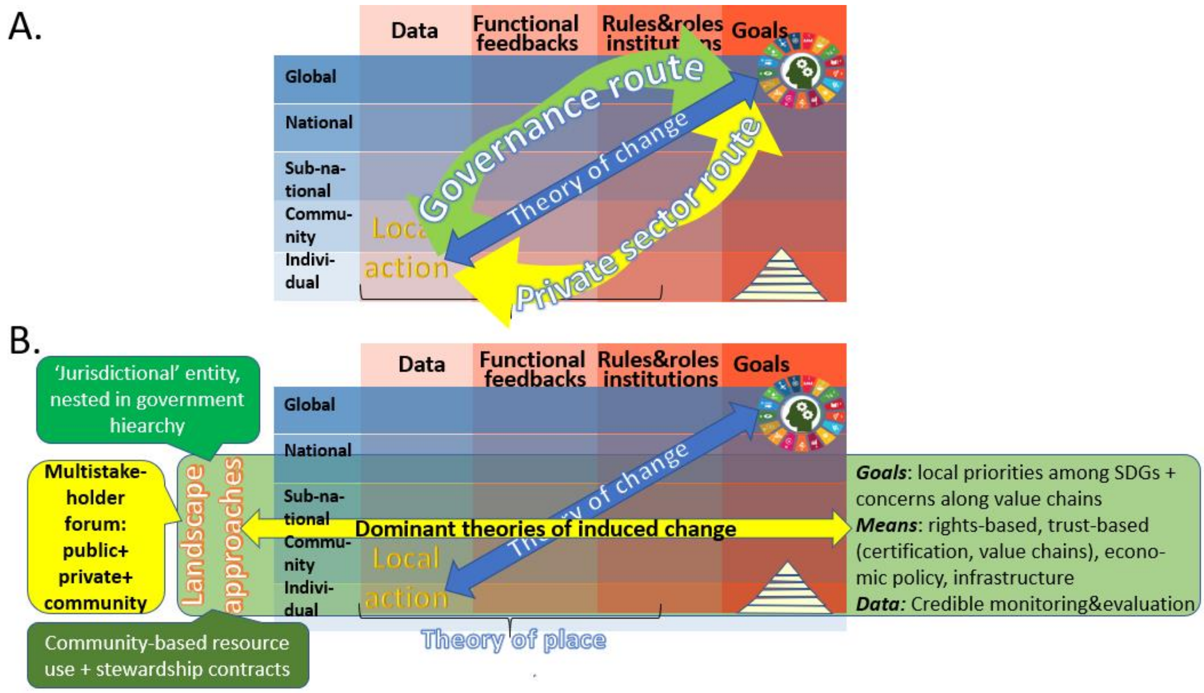

Figure 6. Variations and annotations of Figure 4 that clarify: (A) The dominant "theory of change" on the diagonal connecting local actions to global goals (and vice versa), while theories of place focus on the first two columns, the governance- and private-sector-based parts of theories of change; and (B) a dominant theory of induced change within "landscape approaches" to strengthen the interface between the lowest level of a government hierarchy and bottom-up collective action.

down way) the choices and actions individuals can take to achieve the highest-level goals. Footprints here are used in negotiating the fairness and efficiency of NDCs/individually determined contributions (IDCs) within and between countries.

The cells below the diagonal imply that one first shift from data to feedback processes, to institutions and goals, before moving up the hierarchy from individuals towards governance structures; we tentatively describe this as the private sector, market- or business-based route. In its extreme form (in the ultimate bottom-up way), it recognizes that individual goals drive individual choices and actions and that higher-level goals need to be framed to satisfy demand. Footprints here target the individual and collective decisions of producers, processors/traders, and consumers (IDCs).

In reality, a balance between top-down and bottom-up elements is negotiated across the scales. The global shift of governance systems towards more market-based policies implies attempts to redress the balance, rather than go from one to the other extreme, and has itself been subject to governability checks and balances in political-cultural contexts.

A popular theory of induced change[63] of the past decade has been one of several forms of landscape approach [Figure 6B] at the interface of the lowest jurisdictional level of formal governance structure and the local community, with its diversity of individuals[67-70]. It typically operates in a public-private-people partnership, with informal, negotiated rules, a focus on trial-and-error learning feedbacks, and goals that often are a selective subset of the SDG portfolio. However, according to practitioners, about half of the bottlenecks are caused at the points of interactions with national government agencies[71]. Bridging between the jurisdictional (rule setting) aspects of a connection with formal governance (and often enhanced tenurial security), the private sector partners link to markets and the local community connects to aspirations in a social-cultural context (often including a sense of place or eudaimonia). Clarity on footprint data can provide a solid foundation for landscape-level negotiations with scientific credibility, social legitimacy, and political salience.

Theories of (induced) change concerning carbon footprints

The expectation, or theory of induced change, that transparent and credible footprints will change behavioral choices at individual and collective levels has not been easy to verify. One of the few critical impact studies thus far[72] found that grassroots-initiative members have a 16% lower total carbon footprint and 43% and 86% lower carbon footprints for food and clothing, respectively, compared to their "non-member" regional socio-demographic counterparts in Europe; they also have higher life satisfaction compared to non-members and are 11%-13% more likely to evaluate their life positively. Initiative members uncover lifestyle features that enable lower emissions and break the conventional link among emissions, income, and well-being.

Saujot *et al.*[73] (2020) analyzed explicit knowledge, mediation tools, and framing power as three main contributions that scenario articulation can make to policy decision-making. They discussed an apparent tradeoff between the framing power of integrating lifestyle changes in scenarios and the robustness and reliability of pathway production methodologies, which is a condition for their policy relevance. The nature of lifestyles, which reflect values and preferences and require a multidisciplinary approach, raises significant policy neutrality challenges and scientific challenges. Overcoming these challenges can lead to more policy-relevant pathways, starting with reliable footprint data including indirect effects on emissions and sink strength.

Slogans such as "choose nature, buy less" may appear to be an oxymoron (*contradictio in terminis*) for business models that interact with consumer preferences for responsible (and thus reduced) consumption. However, in a thus far limited niche market, businesses that emphasize efficiency, consistency, and more recently also sufficiency have opportunities to function[74]. Sufficiency aims at an absolute reduction of consumption levels and entails strategies such as decreasing purchases, modal shifts, product longevity, and sharing practices. Benefits for the individuals involved may be primarily social, as in the hedonic-eudaimonic contrast that Ancient Greek philosophers already recognized[64,65].

Discussion and ways forward

This perspective aims to present a framework for analysis that connects the various footprint concepts to theories of place, change, and induced change. Several emerging challenges are described in Figure 7.

Regarding the first question, the operational definition of carbon footprints, several consistency issues emerge. Measured changes in atmospheric GHG concentrations remain the primary consistency check for national accounting of fossil fuel plus land-use related GHG emissions, once structurally missing terms are added[19]. For carbon footprint concepts based on individuals, sectors, or businesses, the first question should be "does it add up?". Consistency issues may easily arise if both "production" and "consumption" actors are considered to make independent decisions, or if the attribution of blame is "to the other side". Similarly, EET remains a major challenge for national accounting systems, as importing countries do not accept them on their balance sheet. However, they are no problems for the lifecycle analysis of products underpinning individual footprints linked to consumer choices. Consequently, the sum of individual footprints can exceed the sum of national footprints.

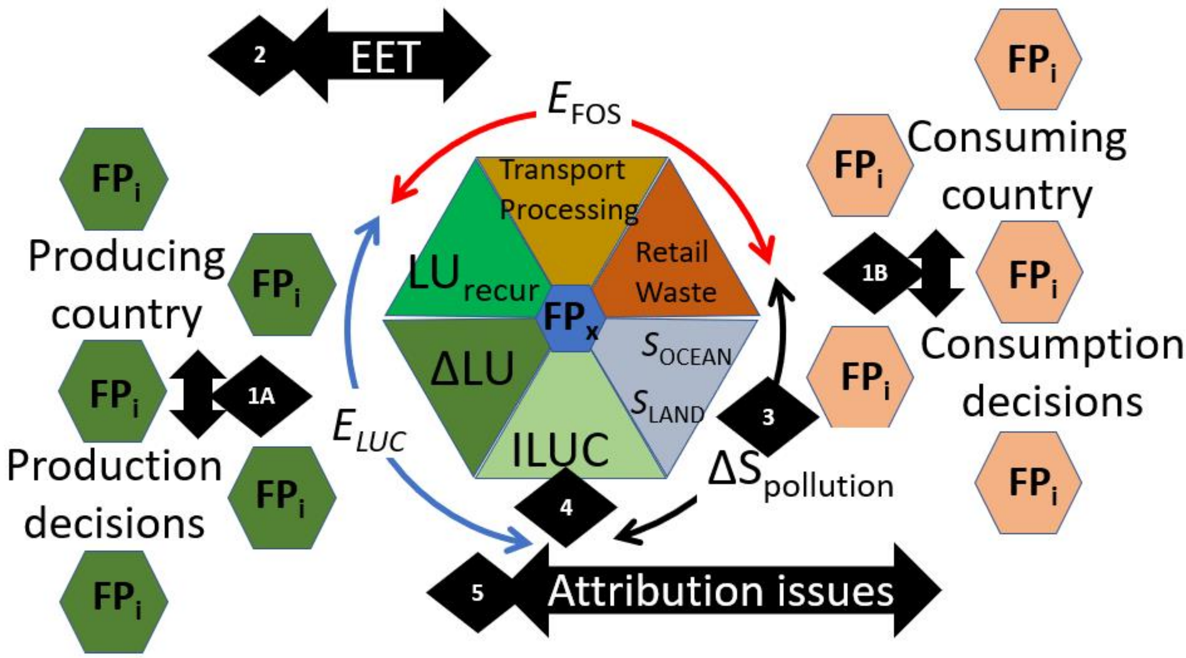

Figure 7. Visualization of challenges to the use of various footprint concepts (FP_i): (1) consistency checks between individual and national footprints across production and consumption; (2) accountability for emissions embodied in trade (EET); (3) incorporation of (avoided) impacts on sink strengths, e.g., based on pollution; (4) the indirect land-use change concept; and (5) further attribution issues in relation to multifunctional land uses.

A single footprint can relate to multiple policy goals at the policy level. For example, soil carbon and wetland preservation commitments have been made under three Rio Conventions: Land Degradation Neutrality (as part of the United Nations Convention to Combat Desertification), climate change (both mitigation and adaptation aspects in the UNFCCC), and biodiversity targets of the Convention on Biological Diversity, in different combinations across the 197 UN member states[75].

The fraction of current emissions that directly contribute to an increase in atmospheric concentrations of GHG, and thus the global climate change per unit emissions, keeps increasing with declining sink strength, with complex attribution issues in the comparison of historical, current, and future emissions. While global Carbon budgets consider emissions from fossil sources (E_{FOS}) plus those from land use (E_{LUC}), negative impacts (e.g., through pollution) on the sink strength of oceans (S_{OCEAN}) and terrestrial systems (S_{LAND}) are not included, and neither are efforts to avoid or repair such negative effects. However, they influence global climate change trajectories and are part of the international policy debate, e.g., regarding forests[76] and ecological restoration[77,78].

The concept of "indirect land-use change" (ILUC) is the most contested aspect within the land use emission category. It emerged in the discussion on biofuels when it was realized that new types of demand for agricultural products, beyond global food supply, would be partially responsible for expansion into new production areas (and thus for emissions associated with such expansion), even if the origin of specific products could be traced to low-emission areas (e.g., not linked to recent forest conversion)[79,80]. In practice, however, ILUC remains controversial as the attribution involves scales beyond the reach of individual producers or consumers and may need to shift to broader product categories. For example, ILUC concepts might attribute the consequences of increased demand to all vegetable oils, rather than a specific one such as palm oil, to reflect the exchangeability of commodities in the current food industry[81]. On the other hand, the conclusion that coconut oil has, in comparison with other vegetable oils, a remarkably high negative biodiversity footprint[82] ignored that in the dataset, 93% of the negative biodiversity impacts were due to small island countries (with vulnerable biodiversity) that only produce less than 10% of global output[83]. Such skewed statistical distributions cannot be ignored in footprint analysis. Agricultural yield elasticity[84] and land sharing in multifunctional land use[85] form additional challenges; in practice, ILUC has not been integrated into standard accounting systems. Accounting for ILUC in footprint calculations depends on inferred causality and highly questionable product categorization. More comprehensive global trade data can help, but their interpretation remains highly political and contested.

On the second question, the way footprints are used as boundary objects in public and private decisions, the view has been expressed that the public appeal and rhetoric value of a single "ecological footprint" concept may well exceed the transparency and reproducibility of current operational metrics. For the carbon footprint component of the overall ecological footprint, the operational issues are less, but the carbon footprint may also be less actionable as tradeoffs with other component footprints exist. One such tradeoff is between carbon storage and water-saving[86]. When economic growth is included in the analysis[87], minimizing any single indicator may not lead to optimal results in the longer term[88,89]. In a similar debate, the water footprint concept has been challenged, with alternatives proposed that have natural vegetation and its water use as a point of reference[90].

Transparent attribution of emissions over drivers can be a strength of footprint quantification, as data on drivers can drive change - if used wisely[91]. Interfaces among footprints deserve attention, as renewable energy production can clash with biodiversity goals, with implications for transitioning to a green economy[92,93]. The interface of biodiversity loss and climate change[94] deserves a search for synergy beyond single footprint concepts. Co-benefits, tradeoffs, and thresholds have been discussed for mitigation policies targeting the agriculture, forestry, and other land use (AFOLU) sectors[95], as well as agroforestry as a land use at the interface[66,96,97]. Geopolitical questions of fairness between countries have their counterparts domestically, with many sectors in developing countries that have high carbon footprints state-owned or fully protected by the state.

Quantitative footprint metrics may be too complex for citizen audiences that prefer a simpler certification of meeting (or not) a set of thresholds for environmentally and socially responsible production, shifting blame to uncertified others[98-101]. Oversimplified policies do not do justice to the complexity of social actors interacting with the unsustainability of agriculture[102]. Global lessons from payment and incentive schemes have suggested that a location-specific form of co-investment in ecosystem services is more feasible than fully result-based schemes using a single metric, such as a carbon footprint[103]. The motivation of national governments to engage in NDCs and voluntarily commit to further reducing emissions from land use may be based on protecting export earnings rather than on climate-related payment schemes as such[104].

Finally, several ideas emerged on how footprint concepts might be improved, including by further research and synthesis. Multifunctionality of land use, a major pathway to reconcile human ambitions and our planet's biocapacity, is still a challenge for common accounting and footprint systems. Carbon footprints may correlate with biodiversity footprints[105], but only partially; however, theories of change are challenged without synergy among ecological footprint components. The irony may be that multifunctional land uses that can contribute to simultaneously addressing multiple problems are not easily assessed, given the various attribution issues mentioned under the first question. This includes the wide range of agroforestry systems that are relevant at the interface of climate change mitigation and adaptation, but not superior in either issue considered separately[90].

CONCLUSIONS

Regarding our first question ("How is the operational definition of carbon footprints related to consistent accounting for GHG, emissions?"), four conclusions emerge:

1. Measured changes in atmospheric GHG concentrations remain the primary consistency check for national accounting of fossil fuel plus land-use related GHG emissions as well as for carbon footprint concepts based on individuals, sectors, or businesses; for any new type of footprints, the first question should be "does it add up?".

2. EET remain a major challenge for national accounting systems but are no problem for Lifecycle analysis of products underpinning individual footprints linked to consumer choices.

3. Negative impacts on oceanic and terrestrial C sinks, or positive effects of reducing pollution or land cover change affecting sinks, remain outside current national accounting as well as common footprint concepts, yet influence global climate change trajectories.

4. ILUC in footprint calculations depends on inferred causality and product categorization that are highly questionable, rather than addressing the drivers.

Regarding the second question ("How are footprint concepts used as boundary objects in public and private decision making?"), we conclude:

5. The public appeal and rhetoric value of footprint concepts may well exceed the transparency and reproducibility of current operational metrics.

6. Carbon footprints as an aspect of human appropriation of net primary productivity (HANPP) are correlated with water footprints and biodiversity impacts that deserve joint responses by consumers, individually and collectively.

Finally, on Question 3 ("How might footprint concepts be improved?"), we conclude:

7 Multifunctionality of land use, a major pathway to reconciling human ambitions and our planet's biocapacity, is still a challenge for common accounting and footprint systems. Other than GHG exchange with the atmosphere, functions that involve lateral flows have specific scaling rules that need to be used to link local to global scales and *vice versa*. Follow-up research can contribute by: (A) testing and improving consistency among footprint estimates, so that they add up to global net emissions; (B) analyzing synergy, tradeoffs, and interactions among various components of an overarching ecological footprint (including aspects with -non-area based scaling); (C) exploring boundary work and the way footprint data are used in societal change; or (D) zooming in on the specific challenges of footprint accounting for multifunctionality of land use in the face of the UN Sustainable Development Goal agenda.

DECLARATIONS

Authors' contributions

Made contributions to the conception and design of the study: van Noordwijk M, Pham TT, Leimona B

Performed data analysis interpretation and writing of the manuscript: van Noordwijk M, Pham TT, Leimona B, Duguma LA, Baral H, Khasanah N

Provided material support: Dewi S, Minang PA

Availability of data and materials

Not applicable.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Rees WE. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* 1992;4:121-130. DOI
2. Wackernagel M, Rees W. Our ecological footprint: reducing human impact on the earth. Available from: http://www.newsociety.com [Last accessed on 15 Apr 2022].
3. Collins A, Flynn A. The ecological footprint: New developments in policy and practice. *Science and Public Policy* 2016;43:725-7. DOI
4. Costanza R. The dynamics of the ecological footprint concept. *Ecological Economics* 2000;32:341-5. Available from: https://www.academia.edu/download/30561355/costanza_20ecofootprint.pdf [Last accessed on 15 Apr 2022].
5. Meadows DH, Meadows DL, Randers J, Behrens WW. The limits to growth: a report for the club of Rome's project on the predicament of mankind. Available from: http://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf [Last accessed on 15 Apr 2022].
6. Allan RP, Hawkins E, Bellouin N, Collins B. IPCC, 2021: summary for policymakers. Available from: https://centaur.reading.ac.uk/101317/ [Last accessed on 15 Apr 2022].
7. Iyer G, Ledna C, Clarke L, et al. Measuring progress from nationally determined contributions to mid-century strategies. *Nature Clim Change* 2017;7:871-4. DOI
8. Haberl H, Wiedenhofer D, Virág D, Kalt G, Plank B et al. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ Res Lett* 2020;15:065003. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/ab842a/meta.
9. Owusu-Sekyere E, Mahlathi Y, Jordaan H. Understanding South African consumers' preferences and market potential for products with low water and carbon footprints. *Agrekon* 2019;58:354-68. Available from: https://journals.co.za/doi/abs/10.1080/03031853.2019.1589544
10. Yu J, Yang T, Ding T, Zhou K. "New normal" characteristics show in China's energy footprints and carbon footprints. *Sci Total Environ* 2021;785:147210. DOI PubMed
11. Pasiecznik N, Savenije H. Zero Deforestation: a commitment to change. Available from: https://library.wur.nl/WebQuery/wurpubs/fulltext/417718 [Last accessed on 15 Apr 2022].
12. Wiedmann T, Minx J. A definition of "carbon footprint". Available from: https://books.google.com.hk/books?hl=zh-CN&lr=&id=GCkU1p_6HNwC&oi=fnd&pg=PA1&dq=Wiedmann+T,+Minx+J.+A+definition+of+%E2%80%98carbon+footprint%E2%80%99.&ots=D1DVEPbgNs&sig=zwy5TSaGzaciaY169IcO2nqfDYs&redir_esc=y#v=onepage&q=Wiedmann%20T%2C%20Minx%20J.%20A%20definition%20of%20%E2%80%98carbon%20footprint%E2%80%99.&f=false [Last accessed on 15 Apr 2022].
13. Carbon Footprint. Scope of this journal. Available from: https://oaepublish.com/cf/pages/view/aims_and_scope [Last accessed on 15 Apr 2022].
14. Fox NJ. Boundary objects, social meanings and the success of new technologies. *Sociology* 2011;45:70-85. DOI
15. Clark WC, Tomich TP, van Noordwij M, Guston D, Catacutan DC et al. Boundary work for sustainable development: Natural resource management at the Consultative Group on International Agricultural Research (CGIAR). *Proc Natl Acad Sci U S A* 2016;

113:4615-22. DOI PubMed PMC

16. Le Quéré C, Rödenbeck C, Buitenhuis ET, et al. Saturation of the southern ocean CO2 sink due to recent climate change. *Science* 2007;316:1735-8. DOI PubMed
17. Hubau W, Lewis SL, Phillips OL, et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 2020;579:80-7. DOI PubMed
18. Friedlingstein P, O'sullivan M, Jones MW, et al. Global carbon budget 2020. *Earth System Science Data* 2020;12:3269-340. Available from: https://essd.copernicus.org/articles/12/3269/2020/essd-12-3269-2020.html [Last accessed on 15 Apr 2022]
19. Smith P, Clark H, Dong H, et al. Agriculture, forestry and other land use (AFOLU). Available from: http://pure.iiasa.ac.at/11115 [Last accessed on 15 Apr 2022].
20. Malik A, Lan J. The role of outsourcing in driving global carbon emissions. *Economic Systems Research* 2016;28:168-82. DOI
21. Meyfroidt P, Rudel TK, Lambin EF. Forest transitions, trade, and the global displacement of land use. *Proc Natl Acad Sci U S A* 2010;107:20917-22. DOI PubMed PMC
22. Minang PA, van Noordwijk M, Meyfroidt P, Agus F, Dewi S. Emissions embodied in trade (EET) and land use in tropical forest margins. Available from: http://www.asb.cgiar.org/PDFwebdocs/PB17_final.pdf [Last accessed on 15 Apr 2022].
23. Henders S, Persson UM, Kastner T. Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/10/12/125012/pdf [Last accessed on 15 Apr 2022].
24. Pendrill F, Persson UM, Godar J, et al. Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change* 2019;56:1-10. DOI
25. Laurent A, Olsen SI, Hauschild MZ. Limitations of carbon footprint as indicator of environmental sustainability. *Environ Sci Technol* 2012;46:4100-8. DOI PubMed
26. Alvarez S, Carballo-penela A, Mateo-mantecón I, Rubio A. Strengths-weaknesses-opportunities-threats analysis of carbon footprint indicator and derived recommendations. *Journal of Cleaner Production* 2016;121:238-47. DOI
27. van Noordwijk M, Dewi S, Minang PA. Minimizing the footprint of our food by reducing emissions from all land uses. Available from: https://www.worldagroforestry.org/sites/default/files/Publications/PDFS/PB16139.pdf [Last accessed on 15 Apr 2022].
28. Seixas J, Ferreira F. Carbon economy and carbon footprint. Available from: https://link.springer.com/chapter/10.1007/978-3-030-58315-6_1 [Last accessed on 15 Apr 2022].
29. Ivanova D, Wood R. The unequal distribution of household carbon footprints in Europe and its link to sustainability. *Glob Sustain* 2020:3. DOI
30. Dubois G, Sovacool B, Aall C, et al. It starts at home? *Energy Research & Social Science* 2019;52:144-58. DOI
31. Gössling S, Humpe A. The global scale, distribution and growth of aviation: Implications for climate change. *Global Environmental Change* 2020;65:102194. DOI
32. Ng R, Yeo Z, Tan HX, Song B. Carbon footprint of recycled products: a case study of recycled wood waste in Singapore. Available from: https://link.springer.com/chapter/10.1007/978-981-4585-75-0_7 [Last accessed on 15 Apr 2022].
33. Niamir L, Ivanova O, Filatova T, Voinov A, Bressers H. Demand-side solutions for climate mitigation: Bottom-up drivers of household energy behavior change in the Netherlands and Spain. *Energy Research & Social Science* 2020;62:101356. DOI
34. Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M, Creutzig F. Quantifying the potential for climate change mitigation of consumption options. *Environ Res Lett* 2020;15:093001. DOI
35. Colglazier W. SUSTAINABILITY. Sustainable development agenda: 2030. *Science* 2015;349:1048-50. DOI PubMed
36. van Noordwijk M, Duguma LA, Dewi S, et al. SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry? *Current Opinion in Environmental Sustainability* 2018;34:33-42. DOI
37. Barbier EB, Burgess JC. Sustainable development goal indicators: Analyzing trade-offs and complementarities. *World Development* 2019;122:295-305. DOI
38. Rockström J, Steffen W, Noone K, Persson Å, et al. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 2009;14:33. DOI
39. Biermann F, Kim RE. The boundaries of the planetary boundary framework: a critical appraisal of approaches to define a "safe operating space" for humanity. *Annual Review of Environment and Resources* 2020;45:497-521. DOI
40. Khasanah N, van Noordwijk M, Slingerland M, et al. Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. *Front Sustain Food Syst* 2020;3:122. DOI
41. Sagar AD, Najam A. The human development index: a critical review. *Ecological Economics* 1998;25:249-64. DOI
42. Wilson EO Half-earth: our planet's fight for life. Available from: http://eqlt.org/wp-content/uploads/2016/10/Spring-newsletter-2017-web.pdf [Last accessed on 15 Apr 2022].
43. Dinerstein E, Olson D, Joshi A, et al. An ecoregion-based approach to protecting half the terrestrial realm. *Bioscience* 2017;67:534-45. DOI PubMed PMC
44. Noordwijk M. Agroforestry-based ecosystem services: reconciling values of humans and nature in sustainable development. *Land* 2021;10:699. DOI
45. Meyfroidt P, Vu TP, Hoang VA. Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the central highlands of Vietnam. *Global Environmental Change* 2013;23:1187-98. DOI
46. Bayrak M, Marafa L. Livelihood implications and perceptions of large scale investment in natural resources for conservation and

carbon sequestration: empirical evidence from REDD+ in Vietnam. *Sustainability* 2017;9:1802. DOI
47. Rockström J, Williams J, Daily G, et al. Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 2017;46:4-17. DOI PubMed PMC
48. Noordwijk M, Brussaard L. Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously? *Current Opinion in Environmental Sustainability* 2014;8:62-70. DOI
49. Struik PC, Kuyper TW. Sustainable intensification in agriculture: the richer shade of green. A review. Available from: https://link.springer.com/article/10.1007/s13593-017-0445-7 [Last accessed on 15 Apr 2022].
50. Noordwijk M, Khasanah N, Dewi S. Can intensification reduce emission intensity of biofuel through optimized fertilizer use? *GCB Bioenergy* 2017;9:940-52. DOI
51. Davis SC, Boddey RM, Alves BJR, et al. Management swing potential for bioenergy crops. *GCB Bioenergy* 2013;5:623-38. DOI
52. Hoekstra AY, Mekonnen MM. The water footprint of humanity. *Proc Natl Acad Sci U S A* 2012;109:3232-7. DOI PubMed PMC
53. Creed IF, van Noordwijk M. Forest and water on a changing planet: vulnerability, adaptation and governance opportunities. Available from: https://agris.fao.org/agris-search/search.do?recordID=XF2018002118 [Last accessed on 15 Apr 2022].
54. van Noordwijk M, van Oel A, Muthuri CW, et al. Mimicking nature to reduce agricultural impact on water cycles: a set of mimetrics. Available from: https://journals.sagepub.com/doi/full/10.1177/00307270211073813 [Last accessed on 15 Apr 2022].
55. Girvan A. Carbon footprints as cultural-ecological metaphors. Available from: https://www.taylorfrancis.com/books/mono/10.4324/9781315621005/carbon-footprints-cultural%E2%80%93ecological-metaphors-anita-girvan [Last accessed on 15 Apr 2022].
56. Hertwich EG, Peters GP. Carbon footprint of nations: a global, trade-linked analysis. *Environ Sci Technol* 2009;43:6414-20. DOI PubMed
57. Wang W, Lin JY, Cui SH, Lin T. An overview of carbon footprint analysis. Available from: http://www.cui-lab.com/qfy-content/uploads/2016/02/e79b86cf8c1c1daf7ad4a4a8121a1db6.pdf [Last accessed on 15 Apr 2022].
58. Meadows DH. Leverage points: places to intervene in a system. Available from: http://drbalcom.pbworks.com/w/file/fetch/35173014/Leverage_Points.pdf [Last accessed on 15 Apr 2022].
59. Ostrom E. Governing the commons: The evolution of institutions for collective action. Available from: https://digitalrepository.unm.edu/cgi/viewcontent.cgi?article=1848&context=nrj [Last accessed on 15 Apr 2022].
60. Kooiman J. Exploring the Concept of Governability. *Journal of Comparative Policy Analysis: Research and Practice* 2008;10:171-90. DOI
61. Thaler RH, Ganser LJ. Misbehaving: the making of behavioral economics. Available from: https://www.interowa.com/support/sites/default/files/anwendungstechnik/lastenheft/pdf-misbehaving-the-making-of-behavioral-economics-richard-thaler-pdf-download-free-book-ba2a7f4.pdf [Last accessed on 15 Apr 2022].
62. Hofstede GJ, Frantz C, Hoey J, Scholz G, Schröder T. Artificial sociality manifesto. Available from: https://rofasss.org/2021/04/08/artsocmanif [Last accessed on 15 Apr 2022].
63. van Noordwijk M. Theories of place, change and induced change for tree-crop-based agroforestry. Available from: https://cgspace.cgiar.org/handle/10568/115511 [Last accessed on 15 Apr 2022].
64. Ryan RM, Deci EL. On happiness and human potentials: a review of research on hedonic and eudaimonic well-being. *Annu Rev Psychol* 2001;52:141-66. DOI PubMed
65. Deci EL, Ryan RM. Hedonia, eudaimonia, and well-being: an introduction. *J Happiness Stud* 2008;9:1-11. DOI
66. van Noordwijk M. Agroforestry as part of climate change response. Available from: https://iopscience.iop.org/article/10.1088/1755-1315/200/1/012002/pdf [Last accessed on 15 Apr 2022].
67. Sayer J, Sunderland T, Ghazoul J, et al. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proc Natl Acad Sci U S A* 2013;110:8349-56. DOI PubMed PMC
68. Minang PA, van Noordwijk M, Freeman OE, et al. Climate-smart landscapes: multifunctionality in practice. Available from: https://books.google.com/books?hl=zh-CN&lr=&id=rii-BQAAQBAJ&oi=fnd&pg=PR12&dq=%C2%A0Climate-smart+landscapes:+multifunctionality+in+practice.&ots=TduM1praen&sig=u1dKItPSfFWUnk8TCoBqYhGfiP4 [Last accessed on 15 Apr 2022].
69. Freeman OE, Duguma LA, Minang PA. Operationalizing the integrated landscape approach in practice. Available from: http://www.jstor.org/stable/26269763 [Last accessed on 15 Apr 2022].
70. Riggs RA, Langston JD, Nerfa L, et al. Common ground: integrated landscape approaches and small and medium forest enterprises for vibrant forest landscapes. *Sustain Sci* 2021;16:2013-26. DOI
71. Langston JD, McIntyre R, Falconer K, Sunderland T, van Noordwijk M, Boedhihartono AK. Discourses mapped by Q-method show governance constraints motivate landscape approaches in Indonesia. *PLoS One* 2019;14:e0211221. DOI PubMed PMC
72. Vita G, Ivanova D, Dumitru A, et al. Happier with less? *Energy Research & Social Science* 2020;60:101329.[PMID:26941687 DOI:10.3389/fpsyg.2016.00234 PMCID:PMC4763027] Caution!.
73. Saujot M, Le Gallic T, Waisman H. Lifestyle changes in mitigation pathways: policy and scientific insights. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/abd0a9/meta [Last accessed on 15 Apr 2022].
74. Gossen M, Kropfeld MI. "Choose nature. Buy less." Exploring sufficiency-oriented marketing and consumption practices in the outdoor industry. *Sustainable Production and Consumption* 2022;30:720-36. DOI
75. Wiese-rozanov L. Soil organic carbon commitments under three Rio Conventions: Opportunities for integration. *Soil Security*

2022;6:100052. DOI

76. Muthee K, Duguma L, Wainaina P, Minang P, Nzyoka J. A Review of global policy mechanisms designed for tropical forests conservation and climate risks management. *Front For Glob Change* 2022;4:748170. DOI
77. Abhilash PC. Restoring the unrestored: strategies for restoring global land during the UN decade on ecosystem restoration (UN-DER). *Land* 2021;10:201. DOI
78. van Noordwijk M, Gitz V, Minang PA, et al. People-centric nature-based land restoration through agroforestry: a typology. *Land* 2020;9:251. DOI
79. Wicke B, Verweij P, van Meijl H, van Vuuren DP, Faaij AP. Indirect land use change: review of existing models and strategies for mitigation. *Biofuels* 2014;3:87-100. DOI
80. Elobeid A, Moreira MM, Zanetti de Lima C, Carriquiry M, Harfuch L. Implications of biofuel production on direct and indirect land use change: evidence from Brazil. Available from: http://www.iecon.ccee.edu.uy/implication-of-biofuel-production-on-direct-and-indirect-land-use-change-evidence-from-brazil/publication/696/en/ [Last accessed on 15 Apr 2022].
81. Khasanah NM. Oil palm (Elaeis guineensis) production in Indonesia: carbon footprint and diversification options. Available from: https://library.wur.nl/WebQuery/wurpubs/fulltext/467425 [Last accessed on 15 Apr 2022].
82. Meijaard E, Abrams J, Juffe-Bignoli D, Voigt M, Sheil D. Coconut oil, conservation and the conscientious consumer. *Curr Biol* 2020;30:R757-8. DOI PubMed
83. van Noordwijk M. Coconut bashing. 2020. Available from: https://www.worldagroforestry.org/blog/2020/07/15/coconut-bashing [Last accessed on 15 Apr 2022].
84. Perkins O, Millington JDA. The importance of agricultural yield elasticity for indirect land use change: a Bayesian network analysis for robust uncertainty quantification. *Journal of Land Use Science* 2020;15:509-31. DOI
85. Azhar B, Nobilly F, Lechner AM, et al. Mitigating the risks of indirect land use change (ILUC) related deforestation from industrial palm oil expansion by sharing land access with displaced crop and cattle farmers. *Land Use Policy* 2021;107:105498. DOI
86. Trabucco A, Zomer RJ, Bossio DA, van Straaten O, Verchot LV. Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. *Agriculture, Ecosystems & Environment* 2008;126:81-97. DOI
87. Hassan ST, Baloch MA, Mahmood N, Zhang J. Linking economic growth and ecological footprint through human capital and biocapacity. *Sustainable Cities and Society* 2019;47:101516. DOI
88. Carter S, Arts B, Giller KE, et al. Climate-smart land use requires local solutions, transdisciplinary research, policy coherence and transparency. *Carbon Management* 2018;9:291-301. DOI
89. Amaruzaman S, Bardsley DK, Stringer R. Reflexive policies and the complex socio-ecological systems of the upland landscapes in Indonesia. *Agric Hum Values*. DOI
90. van Noordwijk, M, Catacutan DC, Duguma L, et al. Agroforestry Matches the Evolving Climate Change Mitigation and Adaptation Agenda in Asia and Africa. In: JC Dagar, SR Gupta, GW Sileshi (Eds.) Agro-forestry for Sustainable Intensification of Agriculture in Asia and Africa. Springer, Berlin. 2022b in press https://link.springer.com/book/10.1007/978-981-15-4136-0.
91. De Sy V, Herold M, Brockhaus M, Di Gregorio M, Ochieng RM. Transforming REDD+: Lessons and new directions. Available from: https://helda.helsinki.fi/bitstream/handle/10138/297080/BAngelsen1801.pdf?sequence=1 [Last accessed on 15 Apr 2022].
92. Gasparatos A, Doll CN, Esteban M, Ahmed A, Olang TA. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews* 2017;70:161-84. DOI
93. McCollum DL, Echeverri LG, Busch S, et al. Connecting the sustainable development goals by their energy inter-linkages. *Environ Res Lett* 2018;13:033006. DOI
94. Pörtner HO, Scholes RJ, Agard J, et al. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. Available from: https://research-repository.uwa.edu.au/en/publications/ipbes-ipcc-co-sponsored-workshop-report-on-biodiversity-and-clima [Last accessed on 15 Apr 2022].
95. Bustamante M, Robledo-Abad C, Harper R, et al. Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Glob Chang Biol* 2014;20:3270-90. DOI PubMed
96. Prasad R, Newaj R, Chavan SB, Dhyani SK. Agroforestry land use: A way forward for reducing carbon footprint in agriculture. Available from: https://www.researchgate.net/profile/Sangram-Chavan-2/publication/335220161_Agroforestry_land_use_A_way_forward_for_reducing_carbon_footprint_in_agriculture/links/5f5f705d92851c078965295b/Agroforestry-land-use-A-way-forward-for-reducing-carbon-footprint-in-agriculture.pdf [Last accessed on 15 Apr 2022].
97. Noordwijk M. Integrated natural resource management as pathway to poverty reduction: Innovating practices, institutions and policies. *Agricultural Systems* 2019;172:60-71. DOI
98. Mithöfer D, van Noordwijk M, Leimona B, Cerutti PO. Certify and shift blame, or resolve issues? *International Journal of Biodiversity Science, Ecosystem Services & Management* 2017;13:72-85. DOI
99. Mithöfer D, Roshetko JM, Donovan JA, et al. Unpacking "sustainable" cocoa: do sustainability standards, development projects and policies address producer concerns in Indonesia, Cameroon and Peru? *International Journal of Biodiversity Science, Ecosystem Services & Management* 2017;13:444-69. DOI
100. Leimona B, van Noordwijk M, Mithöfer D, Cerutti P. Environmentally and socially responsible global production and trade of timber and tree crop commodities: certification as a transient issue-attention cycle response to ecological and social issues. *International Journal of Biodiversity Science, Ecosystem Services & Management* 2017;13:497-502. DOI

101. Leimona B, van Noordwijk M, Kennedy S, Namirembe S, Minang PA. Synthesis and lessons on ecological, economic, social and governance propositions. Available from: https://www.worldagroforestry.org/sites/default/files/chapters/Ch38%20Synthesis%20and%20lessons_ebook_511-538.pdf [Last accessed on 15 Apr 2022]
102. Bernard F, van Noordwijk M, Luedeling E, Villamor GB, Sileshi GW, Namirembe S. Social actors and unsustainability of agriculture. *Current Opinion in Environmental Sustainability* 2014;6:155-61. DOI
103. Namirembe S, Leimona B, van Noordwijk M, Minang PA. Co-investment in ecosystem services: global lessons from payment and incentive schemes. Available from: https://www.worldagroforestry.org/sites/default/files/u884/Ch1_IntroCoinvest_ebook.pdf [Last accessed on 15 Apr 2022].
104. Noordwijk M, Agus F, Dewi S, Purnomo H. Reducing emissions from land use in Indonesia: motivation, policy instruments and expected funding streams. *Mitig Adapt Strateg Glob Change* 2014;19:677-98. DOI
105. Sari R, Saputra D, Hairiah K, Rozendaal D, Roshetko J, van Noordwijk M. Gendered Species Preferences Link Tree Diversity and Carbon Stocks in Cacao Agroforest in Southeast Sulawesi, Indonesia. *Land* 2020;9:108. DOI