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Methods for attributing land-use emissions to products

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Roughly one-third of anthropogenic GHG emissions are caused by agricultural and forestry activities and land-use change (collectively, 'land-use emissions'). Understanding the ultimate drivers of these emissions requires attributing emissions to specific land-use activities and products. Although quantities of land-use emissions are matters of fact, the methodological choices and assumptions required to attribute those emissions to activities and products depend on research goals and data availability. In this review, we explore several possible accounting methods. Our results highlight the sensitivity of accounting to temporal distributions of emissions and the consequences of replacing spatially-explicit data with aggregate proxies such as production or harvested area data. Different accounting options emphasize different causes of land-use emissions (e.g., proximate or indirect drivers of deforestation). To support public policies that effectively balance competing objectives, analysts should carefully consider and communicate implications of accounting choices.

Land-use change and land-use activities are major sources of the anthropogenic GHG emissions that cause climate change, totalling approximately a third (~31%) of all such emissions in recent years [1–3]. Land-use *activities* are practices on land that have some consistent and particular use (e.g., agriculture). Land-use *change* is the conversion of land from one use to another use. Together, net emissions from land-use *activities* and land-use *change* can be referred to as '**land-use emissions**'. A few processes make up most of these land-use emissions: CO_2 emissions result from clearing of forests, when the harvested, cut or disturbed biomass decays or is burned. CO_2 emissions also result from seasonal burning of agricultural residues or prescribed burning of savannas and scrubland. Nitrogen in biomass, animal manure and nitrogenous fertilizers is released from soils as nitrous oxide [4,5]. Methane is produced by enteric fermentation in livestock [6,7], by bacterial methanogenesis during wet rice cultivation [8,9], by anaerobic decomposition of livestock manure [10,11] and in saturated peat soils [12]. Furthermore, different agricultural and forestry practices may result in substantially different land-use emissions [10,13–16]. For example, flooded rice agriculture on land recently cleared of forest where the soil is amended with manure and residues are incorporated in the soil will have a very different emissions profile from an upland rice system using synthetic fertilizers and burning residues between cropping seasons.

At the same time, atmospheric CO_2 is absorbed by growing forests and recovering landscapes, reducing net land-use emissions. Afforestation, rehabilitation of degraded landscapes, replacement of annual crops with perennial crops, incorporation of agricultural residues in lieu of burning, agroforestry and allowing cropland to return to native habitat can all result in net sequestration of carbon.

According to gross estimates for the global terrestrial carbon cycle, approximately 120 Gt C are fixed and sequestered each year by photosynthesis [17,18], which – without human intervention – are approximately balanced by respiration and decomposition (i.e. conversion of biomass carbon to CO_2) [18]. However,

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Key terms

Land-use emissions: GHG emissions from land-use activities and land-use change, collectively.

human land uses have disrupted this balance, reducing uptake and increasing respiration; globally, estimates of net land-use emissions are ~1.1 Gt C year^{-1}[19]. Managing land use in order to decrease GHG emissions and increase sequestration of atmospheric CO_2 is thus an important goal in mitigating global climate change, but this entails considering diverse biological processes and balancing these climate-related goals with food and timber production, biodiversity conservation and provision of ecosystem services.

Aims and scope

The millions of individual management decisions that together determine the magnitude of global net land-use emissions are influenced by a complex set of factors. At present, major research efforts are focused on assessing socio-economic drivers of land-use emissions such as changes in population [20], economic development [21–23], expansion of transport infrastructure [24,25], consumption patterns (e.g., dietary shifts) [26,27], access to international markets [28] and policy [29–32]. Increasingly, such research seeks to ascribe land-use emissions to particular agricultural systems or crops. Such attributions are an important step towards isolating drivers of land-use emissions, raising awareness about ecological impacts of various products and practices and identifying intervention points for climate and land-use policies; nevertheless, assigning land-use emissions to specific crops or products is not straightforward. Moreover, the analysts working to attribute land-use emissions are incredibly diverse, working in fields of ecology, climate science, lifecycle assessment, forestry and agronomy. And unfortunately for decision-makers trying to interpret such attributions, the methods, terminology and perspectives of these different analysts are equally diverse. For instance, lifecycle analysts commonly focus on a specific product (a 'functional unit') and work upstream through the value chain estimating material and energy demands and environmental impacts, including relevant land-use emissions [33,34]. In contrast, ecologists and climate scientists often begin with regional or national estimates of land-use emissions and seek to assign these emissions to downstream products and consumers [35–37]. This review is especially intended to benefit analysts taking the latter approach.

The aim of this review is to present and assess several different methodological options for assigning land-use emissions to activities or products considering data availability and the goal of accounting. As part of the analysis and discussion, we also propose a conformed terminology that, if adopted, will be useful to those performing, describing and interpreting accounts of land-use emissions.

Attributing land-use emissions – and especially those emissions related to land-use change – to products entails many assumptions and value judgements. And often, these assumptions and values are not explicitly communicated. Figure 1 & 2 are decision trees of the main options analysts face when attributing land-use emissions to specific actions and products. These decisions also reflect the organization of this paper. We begin with a brief introduction to the processes that must be considered when calculating land-use emissions, and then discuss options for distributing these emissions in space and time (the first step of allocation; Figure 1). We then assess different methodologies for allocating these spatially and temporally resolved emissions to specific actions or products (Figure 2). Next, we discuss the substantive differences that result from these specific accounting decisions through an extended example (Figure 3–5). Finally, we conclude with a discussion of future emissions accounting exercises.

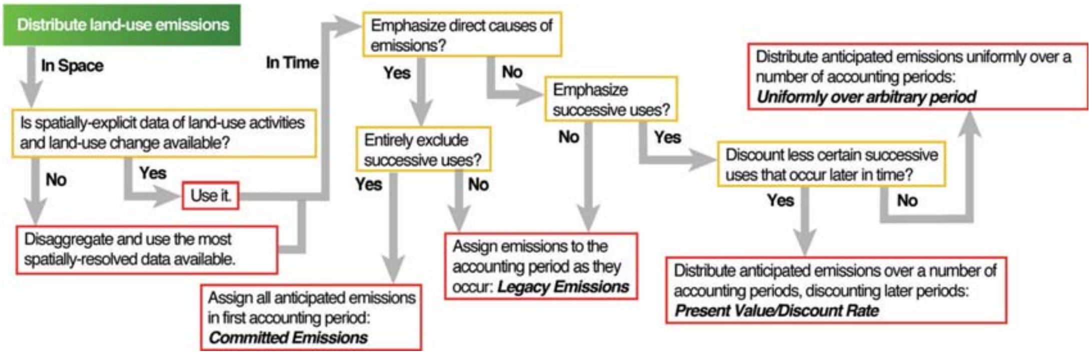

Figure 1. Decision tree of options in distributing land-use emissions in space and time.

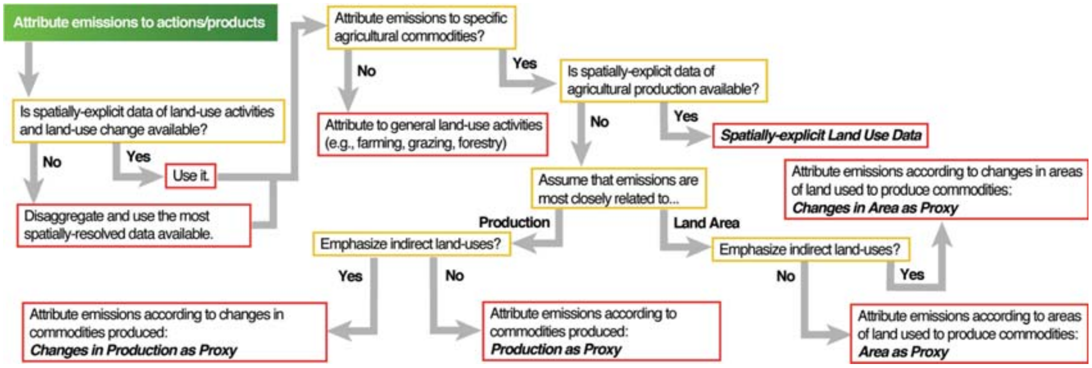

Figure 2. Decision tree of options in attributing emissions to specific actions or products.

Land-use emissions

Agricultural emissions

The predominant land-use *activity* globally is agriculture. In 2011, 4.9 Gha globally were devoted to agriculture, or just over 37% of all land area [38]. By comparison, the global footprint of cities is only about 0.5% of total land area [39]. Agricultural emissions refer to emissions directly linked at the field level to the production cycle of crops and livestock. Globally, N_2O emissions from the application of synthetic and organic fertilizers, CH_4 from enteric fermentation in livestock, manure management and rice cultivation were estimated to total 4.6 Gt CO_2-e in 2010 [3], and CO_2 from burning grasslands and agricultural waste in 2009 were 0.7 Gt C [40]. Such agricultural emissions are coincident in time and space with agricultural production (see Figure 3A). For example, while some of the nitrogen in fertilizer applied to a field is being taken up by growing crops, microbial nitrification and denitrification eventually converts a fraction of that nitrogen (on the order of 1%) into N_2O at short timescales [41]. Production of the crop (the product for attribution) and the N_2O (the emissions to be attributed) occur at the same time and in the same field. In the same way, CH_4 emissions from enteric fermentation in beef cattle (and the decomposition of related manure) will be produced near in time and space as to the beef, just as agricultural residues will usually be burned in the field. Thus, agricultural emissions can often be readily linked to the crop or animal product being produced, as prescribed by the IPCC Guidelines for National Greenhouse Gas Inventories [41] (bearing in mind that such attributions are still estimates with associated uncertainties; direct measurements of land-use emissions by chamber and eddy-covariance measurements exist for very few places and for very limited times).

However, not all agricultural emissions take place at the field level during the production cycle of the crop or animal. Some of the biomass produced by agriculture (e.g., food crops) may be transported long distances to the point of consumption, where the biomass is oxidized [42,43], which results in a spatial dislocation of emissions. Other biomass (e.g., crop residues) may decay over a period of years [44] or be used much later as a fuel, resulting in a temporal dislocation. Insofar as transport of biomass displaces CO_2 emissions in space or protracted decay results in substantial CO_2 emissions beyond a single accounting period, these emissions will introduce new complexity in attribution (see discussion on distributing emissions in space and time later in the paper).

3.2 Forestry emissions

Roughly half of global forests, about 2 of the total 4 Gha, are used by humans as a source of wood and non-wood products [45]. The term 'forestry' refers to management of these forested areas. The production of forest products causes emissions in two ways: first, similar to agricultural emissions, fertilization and other management in particular on plantations may lead to non-CO_2 GHG emissions (e.g., N_2O and CH_4); second, logging and wood harvest involves long-term disturbances of the carbon cycle that may lead to CO_2 emissions and uptake spanning many accounting periods. Similarly, afforestation and regrowth will span many accounting periods. In addition, harvested wood is often transported long distances and transformed into secondary or tertiary products before its biomass carbon is oxidized [43]. Wood in buildings, structures, ships and furniture may take decades to ultimately decay (see discussion later in the paper).

Land-use change emissions

Just as is sometimes the case with agricultural and forestry emissions, CO_2 emissions following a change in land use (i.e., 'land-use change' emissions) often occur at times or places that are widely separated from the time and place of land-use change. For example, when an area of forest or savanna is cleared for use as cropland (deforestation), the cleared biomass may have many different fates. For example, biomass is often burned immediately *in situ*, but it could also be left to decompose slowly, such that its carbon will oxidize to CO_2 over a number of years to occur (e.g., see area shaded red in Figure 3B), or some of the biomass may be removed from the area and transported elsewhere, as in the case of forest products.

It should be noted that there are substantial uncertainties associated with estimates of every type of land-use emission. A detailed treatment of such uncertainties and their quantification is included, for instance, in the IPCC guidelines [41]. While the magnitude of such uncertainties has implications on its own [46], in this paper we focus on attributing the uncertain estimates of land-use emissions to specific agricultural and forestry products.

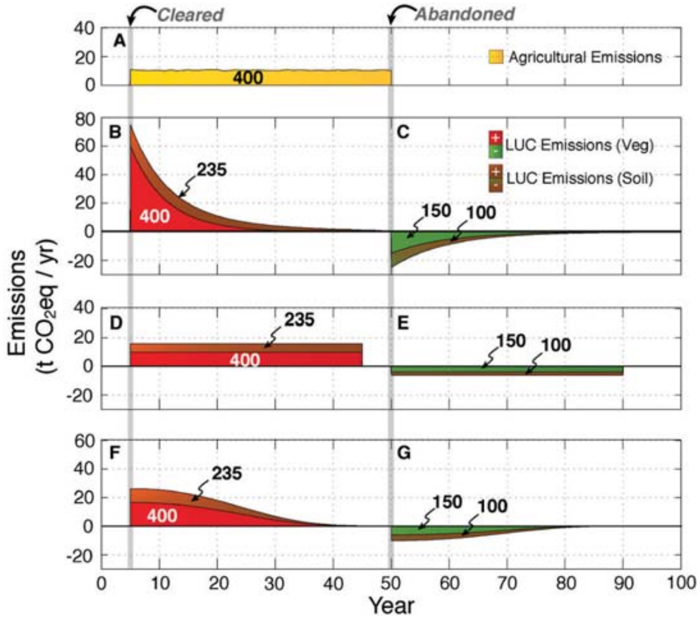

Figure 3. Idealized temporal distribution of (A) agricultural emissions and (B) land-use change emissions from 1 ha of forested land that was cleared in year 5 and then farmed or grazed for a period of 45 years until (C) it was abandoned and native forest allowed to regrow, resulting in carbon sequestration. Although agricultural emissions **(A)** are relatively constant during managed use of the land (depending on the type of agricultural system, crop type and practices in use), land-use change (LUC) emissions after conversion of primary forest may be unevenly distributed in time (e.g., **B**). A likely scenario **(B)** is exponential decrease in the years after the clearing with some emissions continuing to year 30 and beyond [41]. The uptake of carbon after abandonment (beginning in year 50, **C**) may be similarly uneven, as vegetation regrows and soils mature at different rates. Panels **(D)** and **(E)** show the same LUC emissions distributed uniformly over a 40-year period, and panels **(F)** and **(G)** show the same LUC emissions distributed according to a 'carbon net present value' scheme with a discount rate of 5%, which results in a convex-down curve that distributes a greater proportion of LUC emissions in the early years after a clearing, but not as large a proportion as in panels **(B)** and **(C)**.

While the changes in carbon stored in biomass on a given area of land may happen at varying timescales, the slow adjustment of soil carbon pools to altered levels of vegetation happens on even longer timescales of several decades [44,47] (e.g., see areas shaded brown in Figure 3B). Meanwhile, generations of different crops may have been cultivated and harvested, with residues burned or incorporated, on the new cropland. For these reasons, assigning land-use change emissions from an area of land to specific agricultural products related to that area is complex and dependent upon a number of analytical assumptions.

Distributing land-use emissions in space

The first step in any assignment of land-use emissions to products is to quantify the net emissions to be assigned in space (Figure 1). The spatial resolution of such quantification will most likely depend upon data availability. For instance, Carlson *et al.*[48] use satellite imagery to resolve land uses at the scale of individual oil palm plantations in Indonesia, while Karstensen *et al.*[37] estimate land-use emissions at the scale of Brazilian states using aggregate deforestation data. The IPCC guidelines include detailed guidance on estimating land-use emissions from a geographical area of interest even where spatially-explicit data of land-use activities and land-use change are not available [41].

■ Displaced emissions

When agricultural, forestry or waste products are transported from the land where they are produced to a different area where they are subsequently converted to CO_2 (e.g., by burning), it must be decided whether the resulting GHG emissions will be distributed to the region or parcel where the products originated or to the region or parcel where the GHG were emitted. Few studies have attempted to determine the location of emissions (i.e., the destination of transported land-use products and waste) (but see, e.g., [42,43]). Instead, CO_2 emissions from biomass removed during harvest or clearing of land are most often assumed to have been oxidized within the same region as the land-use activity. This assumption is consistent with the Tier 1 approach under IPCC guidelines, although the guidelines propose and discuss more complex options (e.g., atmospheric flow, stock-change and a 100-year method) (see Vol. 4, Chap 2 and 12 in [41]).

Distributing land-use emissions in time

After land-use emissions have been quantified for a given region of interest, the emissions must be distributed in time (Figure 2). Where all the land-use emissions of interest occur within a single accounting period (e.g., 1 year), it is simple to assign all the emissions to that time period. But where actions taken in one accounting period result in emissions that span multiple accounting periods, there are several options for distributing the emissions in time. These options may also be used to distribute emissions that occur within a single accounting period over time in order to emphasize successive uses, for example, after a natural forest fire.

Figure 3 shows a 100-year timeline for a hypothetical hectare of forested land that is cleared in year 5 to use as cropland, then farmed or grazed in a relatively steady-state manner for 45 years and finally taken out of production and allowed to regrow in year 50. Agricultural emissions for this plot of land are shown in Figure 3A, with different options for distributing land-use change emissions (both biomass and soil) in time in the subsequent panels. These options are discussed in subsequent sections.

▪ Committed and legacy emissions

A number of previous studies have discussed the temporal distribution of land-use change emissions, and have defined some useful terms: **Committed emissions** are all the future emissions that will result from a change in land use regardless of when those emissions will occur or the integral of the emissions curves in Figure 3B (and D & F) [48,49]. Note, however, that where future emissions may vary depending upon management and subsequent changes in use (e.g., abandonment of the land), it may be difficult or impossible to accurately quantify such committed emissions. **Legacy emissions** are emissions occurring at any given time and that are the result of a specific change in land use that occurred in the past [37,50]. Figure 3B shows how legacy emissions related to a land-use change might be distributed in time according to our understanding of how the carbon cycle reacts to land-use conversions. The figure portrays an idealized, but likely qualitatively accurate, time distribution of emissions that would arise from a large, single act of native habitat clearing.

Approximating the carbon response described by Houghton *et al.*[44] for temperate deciduous forest, initial stocks of carbon in vegetation and soils are each assumed to be ~110 tons of C (400 tons CO_2); ~40% of the carbon in vegetation oxidized is assumed to be oxidized at the time of clearing, ~33% transferred to the soil pool and ~27% oxidized over the next 10 years. Of the initial soil carbon (including transferred vegetation carbon), ~55% is oxidized in the first 15 years after the clearing, and an additional ~7% is oxidized over the following 15 years [44]. Thus, in this example, most of the emissions associated with the land clearing would occur within a few years, as biomass is burned to rapidly clear the land or used as fuelwood within a few years. Some woody biomass, however, might be left on site as long-lived harvest residues or be hauled off and used for furniture or shipping crates or other longer-lived products, which decay slowly or are burned at the end of their lifetimes, whether as fuel or simply as a means of disposal (see, e.g., the long tail of emissions in time in Figure 3B). Conversely, when human use of the land ends (i.e., the land is abandoned), there is fast initial regrowth (sequestration) with net carbon fluxes that trend towards zero as the forest or native habitat approaches a quasi-equilibrium state (in the absence of environmental changes; Figure 3C). Net zero emissions can occur either because the land cover has returned to its initial, full growth state or when it has recovered to some degraded state of secondary vegetation.

Key terms

Committed emissions: The sum of all emissions, including future emissions, expected to result from a change in land use.

Legacy emissions: Emissions in a place and time that relate to a past change in land use.

While the emissions profiles shown in Figure 3B & C are qualitatively plausible, information on even the approximate curvature for any particular land conversion, let alone all conversions across space and time, is in most cases unavailable. Actual land-use emissions must therefore be estimated, for instance, by defining response functions that reflect our knowledge of carbon dynamics, often composed of stepwise linear or exponential equations for the individual carbon pools involved [1]. These can be generally applied to transitions in order to estimate legacy fluxes over time for both emissions and sequestration (i.e., Figure 3B & C) or summed to estimate committed emissions. Committed emissions can also be redistributed in time according to other methods. Two other options are described in the following sections.

▪ Uniformly distributed over arbitrary period

One possible choice is to distribute committed emissions (either positive or negative) uniformly over a given time period(see Figure 3D & E). An obvious benefit of this method is its relative conceptual simplicity (facilitating ease of communication and methodological transparency) and computational ease. For this reason, product carbon footprint standards such as PAS 2050 and the GHG protocol suggest this method [51,52]. The one degree of freedom in the calculation is the total time period of distribution; once this period is chosen, annual emissions are simply the committed emissions divided by the number of years. In addition,

Key terms

Uniformly distributed emissions: Committed emissions distributed uniformly over an arbitrary period of time (e.g., 20 years).

Future discounted: Committed emissions distributed over some period according to a net present value concept that assigns more emissions to earlier times (i.e., discounts the future).

this method may be preferred in cases where a land-use succession is expected because the time period may be chosen to ensure that later uses are attributed emissions even if legacy emissions decay to near zero prior to those later uses. For example, deforestation in the Brazilian Amazon has historically been driven by livestock in the short term (i.e., forested land is converted to pasture land). However, pasture is often then converted to cropland within a few years, with the rapidity of forest–pasture–cropland succession varying by region (but note that in some regions forest is increasingly being converted directly to cropland) [53,54]. In the forest–pasture–crop succession case, an exponential decay model would attribute a large portion of emissions to the first use(i.e., pasture)after clearing, even if the second use(i.e., cropland)was initially anticipated and intended. Depending on the choice of time horizon, uniform distribution of committed emissions may attribute a greater proportion of committed emissions to foreseeable later land uses and avoid disproportionately attributing emissions to land use immediately following a change. Patterns of successive uses are common. For instance, in Indonesia, logging is expected to lead to oil palm plantations within a few years [48,55], and in Vietnam forest cleared for shifting subsistence agriculture is routinely taken over by coffee plantations [56]. In such cases, analysts could conceivably distribute emissions in time according to whether and to what extent the successive uses are foreseeable or intended by the parties who are clearing land.

▪ Other depreciation scheme, present value/discount rate

The other option for distributing emissions in time is illustrated in Figure 3F & G, where the distribution of emissions is weighted towards the present time using the financial accounting concept of net present value and an arbitrary discount rate of 5%. Previous studies have applied the concept to value avoided emissions, carbon sequestration, and conserved habitats [e.g., 57, 58–60]. As with **uniformly distributed emissions**, such a 'carbon net present value' method is subjective and uncoupled from physical estimates such as legacy emissions. The benefit of the carbon net present value method is that it has a longer 'vision' than exponential decay and may more accurately attribute emissions to succession crops or secondary land uses that may have been anticipated or intended; at the same time, it captures some of the decay in emissions attribution that makes qualitative sense in the exponential case. As with financial accounting, this method is very sensitive to choice of discount rate; unlike financial accounting, however, where a local interest rate often serves as a default value, there is no obvious choice in the carbon net present value method for the discount rate. Rather, as where emissions are distributed uniformly over an arbitrary period, the choice of discount rate should be made – just as the choice to change land use is – in consideration of the foreseeable succession of land uses, perhaps informed by interviews, statistical analyses of recent land-use patterns, economic modelling or even agent-based modelling of local decision-making [61].

Each of the four proposed methods – committed, legacy, uniformly distributed, and **future discounted** (see Figure 4) – includes further choices that multiply the option space. A key issue is the treatment of legacy emissions after an area is transformed from one use to another, for example, when the maize fields of Figure 4A are converted to soybean field or when an agricultural fields are abandoned (i.e., active use ends). Some of the legacy emissions will cease upon a further transformation, for example, the slow adjustment to new soil carbon levels from a forest to crop transformation will stop once cultivation of the land ends (i.e., the cropland is abandoned), but other emissions will not, for example, the decay of harvest residues and products will continue. If detailed carbon flux data is not available, the end-member choices are to fully cut off or to fully transfer all legacy emissions and adjust the quantity of emissions that are distributed in space and time. Such a choice is not necessary in Figure 4 because no land is abandoned in the example.

Attributing land-use emissions to actions/products

▪ Spatially-explicit land-use data

Both committed emissions and legacy emissions have been used in the cited studies to attribute land-use change emissions to specific agricultural products. Carlson *et al.*, for instance, assumed that all the carbon in aboveground biomass of forest that was cleared was immediately oxidized, and if the cleared area was planted with oil palm, they assigned all of these CO_2 emissions to oil palm ('commitment accounting') [48]. In contrast, Karstensen *et al.* sought to assign legacy emissions occurring in a given year to crops produced in the same year ('legacy accounting') [37]. However, directly linking committed or legacy emissions to crops requires spatially-explicit data or assumptions regarding what crops are being grown where. And because of the difference in how emissions are distributed over time, the two approaches may lead to quite different conclusions. For example, Figure 4A shows a simplified spatial pattern of agriculture in an area of 4 ha over time. Assuming the emissions in Figure 3B are from this

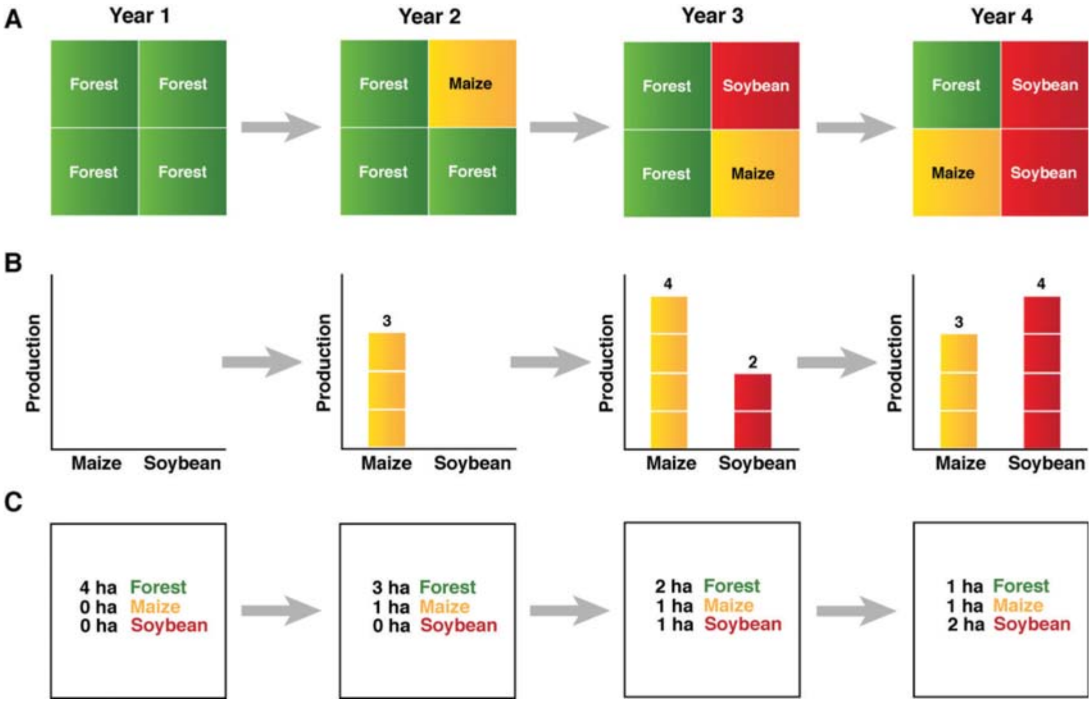

Figure 4. (A) An idealized, spatially-explicit progression of land use and crops grown in a 4 ha area over a 4-year period. (B) The production (e.g., mass or economic value) of crops produced in each corresponding year. (C) Aggregate areas of forest, maize and soybeans in each year.

area, commitment accounting would attribute all emissions from initial clearing of forest to maize and none to soybean because in the Figure 4A example soybean always replaces maize and never forest. How to assign land-use change emissions where production systems are routinely displaced, as in Figure 4A, is a recognized problem with commitment accounting [62]. But legacy accounting may have similar problems because, in the Figure 4A example, it would attribute the majority of emissions to maize during the first year after clearing, and much less to the soybeans grown later.

Allocating land-use emissions to specific products is further complicated because spatially-explicit agricultural data (Figure 4A) are frequently unavailable and tend to exist only at smaller scales, such as where detailed remote sensing products have been created to monitor a particular area or land-use trend. An example of this is the work on oil palm plantations in Indonesia by Carlson *et al.* [36,48]. Such detailed data are often unavailable, especially at larger scales of analysis. In such cases, several alternative methods of assigning emissions to specific products exist.

It should be noted that attributing land-use emissions to specific products may not be necessary, for instance, where the results are for a national inventory as opposed to a life cycle analysis. Here, we are assuming that the analyst is attempting to be as specific as possible in her attribution.

Production as proxy

Where information about crops or livestock grown on specific land parcels is not available, it may be possible to distribute emissions from a region according to the quantity of agricultural goods produced in that region. For example, the UN FAO collects and publishes data on the mass of agricultural goods produced by nations [38]. This method of allocation rests on an assumption that land-use emissions are correlated with agricultural production. For example, Figure 4B illustrates production from the 4 ha area in Figure 4A in each of 4 years. In year 3, two-thirds (four units) of the production is maize and one-third (two units) is soybean. Thus, if emissions were being assigned based on this production, two-thirds of the emissions of year 3 would be attributed to maize and one-third to soybean (with the total emissions in that year of course depending upon how emissions were being distributed in time). In this example, the absence of spatially-explicit production data makes the issue of temporal distribution less salient. Although Figure 4A shows that forest is converted to maize production in years 2, 3 and 4, the production of maize is relatively constant over the same period. If, in this example, all future (committed) emissions were assigned according to production, some emissions would be assigned to soybeans even though soybean agriculture was never the proximate cause of forest clearing.

The units of production need not be mass, although that is likely to be the most readily available data. For instance, emissions might logically be assigned in proportion to the economic or monetary value of produced goods. Or, production might be measured according to the nutritional value of the agricultural good produced, whether calories, protein, fat, etc. If the accounting of land-use emissions were ultimately intended to support climate policy, these different alternatives would reflect different priorities and intervention points for policy. That is, assigning emissions based on economic value might make sense where policymakers seek to distribute the burden of climate policy according to the ability of different farmers, land managers and consumers of agricultural and forest products to pay. In contrast, assigning based on the mass of goods produced or the nutritional value of those goods might make sense where policymakers seek to distribute the burden of climate policy according to the energy or industrial effort of production or, in this case of nutrition, according to some attributed 'public policy value' of the goods.

Lastly, given the dynamic nature of *change* in land use, it may be possible and desirable to assign emissions based on *changes* in the quantity of agricultural goods produced in the relevant region. For example, the idealized example in Figure 4B would assign emissions from year 3 according to changes in production between years 2 and 3: one-third (4 – 3 = 1 unit) to maize and two-thirds (2 – 0 = 2 units) to soybean. Using change in production as a basis for allocation requires that other causes of change be considered in order to avoid unintended distortions in how emissions are assigned. For example, if environmental conditions or a new disease or pest diminish the production of a specific crop in successive years, and farmers respond by clearing forest and planting more of that crop, production of that crop might not change much while its expansion was nonetheless prompting substantial land-use change and emissions.

▪ Area as proxy

Another alternative where spatially-explicit data of agricultural production is unavailable is to assign emissions according to the land areas dedicated to different agricultural goods. For example, Saikku *et al.* allocate Brazilian land-use change emissions to exported biomass products based on the area occupied by their production [63]. This method of allocation assumes that land-use emissions are closely related to land area. Figure 4C shows the overall number of hectares of forest, maize and soybeans within the example area, but not which crop is on which hectare (as shown in Figure 4A). Such aggregated area data is analogous to the information collected and published by the FAO on the areas of different crops harvested in each country [38]. Because land use is inherently spatial, it is intuitively appealing to distribute land-use change emissions according to the areas being used to produce different agricultural goods. As an aggregate perspective of how a region's land is being used, this method neglects the details of how one use succeeds another and arguably assesses the underlying drivers of land-use change regardless of proximate cause. For example, Figure 4C shows no increase in the area of maize after year 2 even though forest is cleared for maize in years 3 and 4 (Figure 4A), while the area of soybeans grows in years 3 and 4 even though no forest is directly replaced by soybeans (Figure 4A). Such issues are particularly relevant in areas of where crops are commonly rotated, where one land use frequently displaces another, or where shifting cultivation is common practice.

While the different quantities of production (e.g., mass, economic value, nutrition) are indirect metrics meant to indicate how productively land is being used, area is a direct and indivisible characteristic of land use. Allocating emissions by land area used therefore introduces no new characteristics. Policies based on this method would therefore tend to encourage emissions reduction by intensification of land use [64].

Just as with production, it is also possible to allocate emissions not only by the land areas used but also by the *changes* in areas used. For example, carbon emissions to the atmosphere would be allocated according to positive changes in used areas (i.e., expansions) and carbon taken up from the atmosphere and stored in biomass would be allocated to expansions of regrowing (net sequestering) areas. Again using the example in Figure 3C, the change in area of maize from years 2 to 4 is zero, while the change in area of soybeans over the same period is 1 ha per year. Thus, all land-use change emissions from conversion of forest in those years would be assigned to soybeans. This result is even more extreme in linking land-use change emissions with the indirect causes of land-use change.

Other issues in attributing land-use emissions

▪ Indirect land-use change

It is generally understood that land use in one place may drive land-use change in other places. For instance, it might be inferred from Figure 4 that by switching the upper right hectare from maize to soybeans in year 3 caused conversion of forest in the lower right hectare to cropland growing the displaced corn. Given global economic markets, such displacements may span great distances and national boundaries. No matter the distance, this linkage is often referred to in the literature as 'indirect land-use change' or 'leakage'[65–70]. There remains considerable debate over whether and how such indirect land-use change emissions ought to be accounted for and to which activities or products it should be attributed. In this paper we have demonstrated that different attribution methods (e.g., *change* in areas dedicated to different uses) may emphasize indirect drivers of land-use change.

Permanence

Some policies and programmes designed to avoid deforestation or induce afforestation (e.g., the UN REDD Programme) financially compensate land managers to conserve standing forest or regrow forest. In these cases, there is an issue of 'permanence' or how to ensure that these forests will not later be cleared for agriculture [71,72]. Although this review is not aimed at informing these sorts of programmes, the different accounting methods discussed and shown in Figure 3C, E & G could conceivably be used to distribute the emissions that will be sequestered by regrowing forests over time in the future (and perhaps the corresponding compensation to land managers).

Intermediate goods and trade

After assigning land-use emissions to particular agricultural and forest products, it may also be of interest to assess where and how the products are consumed [21,37,42,43,63,73,74]. In some cases, consumption-based accounting of land-use emissions will highlight issues of indirect land-use change mentioned above. For example, consumption of maize in a country may remain constant even while production of maize in the country decreases if compensated for by imported maize. A production-based accounting of land-use emissions would show a decrease in agricultural emissions in that country, but would miss the fact that *demand* from that country resulted in land-use emissions elsewhere (a classic example of emissions leakage) [75–77]. A consumption-based accounting system would attribute the land-use (and transport) emissions to the country where agricultural and forest products are ultimately consumed.

Such analysis entails methods such as environmental input–output modelling that are beyond the scope of this paper, except to recognize that there are also methodological alternatives in those cases, as well. For instance, do the land-use emissions assigned to soybeans ultimately transfer to the meat of animals fed with the soybeans? What if the meat is processed and becomes an ingredient to some other food product? What if that food product is only partially consumed and is disposed of in a landfill where it eventually decomposes anaerobically to CH_4? Methods such as input–output modelling may be able to track and assign the original land-use emissions to either intermediate steps in the supply chain (e.g., bilateral trade analysis as in [37,74]) or to the final consumer (e.g., multiregional input–output analysis as in [43,75]). However, available data on international trade is often aggregated into broad sectors such that it may be difficult to draw meaningful conclusions about specific products.

Conclusions

Figure 5 demonstrates the large differences in how land-use change emissions may be assigned to crops depending upon the accounting method used. The emissions are assigned to maize and soybeans assuming use of a 4 ha area that follows the example shown in Figure 4 and assuming that the land-use change emissions per hectare of forest cleared correspond to those shown in Figure 3B. As the first column of Figure 5 shows, assigning all future emissions in the first year after clearing – committed emissions – leads to very large annual emissions in the years when clearing occurs (but none afterwards). The other columns essentially reflect the extent to which land-use change emissions are spread out in time: exponential decline of emissions as mediated by the natural carbon cycle (column 2, legacy emissions) leads to quite large emissions in the early years after clearing, whereas uniformly distributing the land-use change emissions over 40 years (column 3, uniformly distributed) leads to quite small emissions that (not shown) extend further into the future. Considering the different approaches to assigning emissions to products, we find that allocation by production and by land area (rows 2 and 4, respectively) reasonably approximate the allocation where spatially-explicit data is available (row 1). In contrast, allocating by *change* in production or *change* in land area assigns more emissions to the indirect driver of land-use change in the example, which is soybean farming.

This review has presented a variety of methods for assigning emissions from land-use activities to particular agricultural goods, considering the distribution of the emissions over time and techniques for attributing the emissions to produced goods in the absence of perfect information about exactly which parcels of land were required to produce the goods. Each of these methods has its own advantages and limitations and offers different potential insights into the relationship of human land-use activities and the resulting emissions. Further, no single method can be called correct; they are accounting methods devised

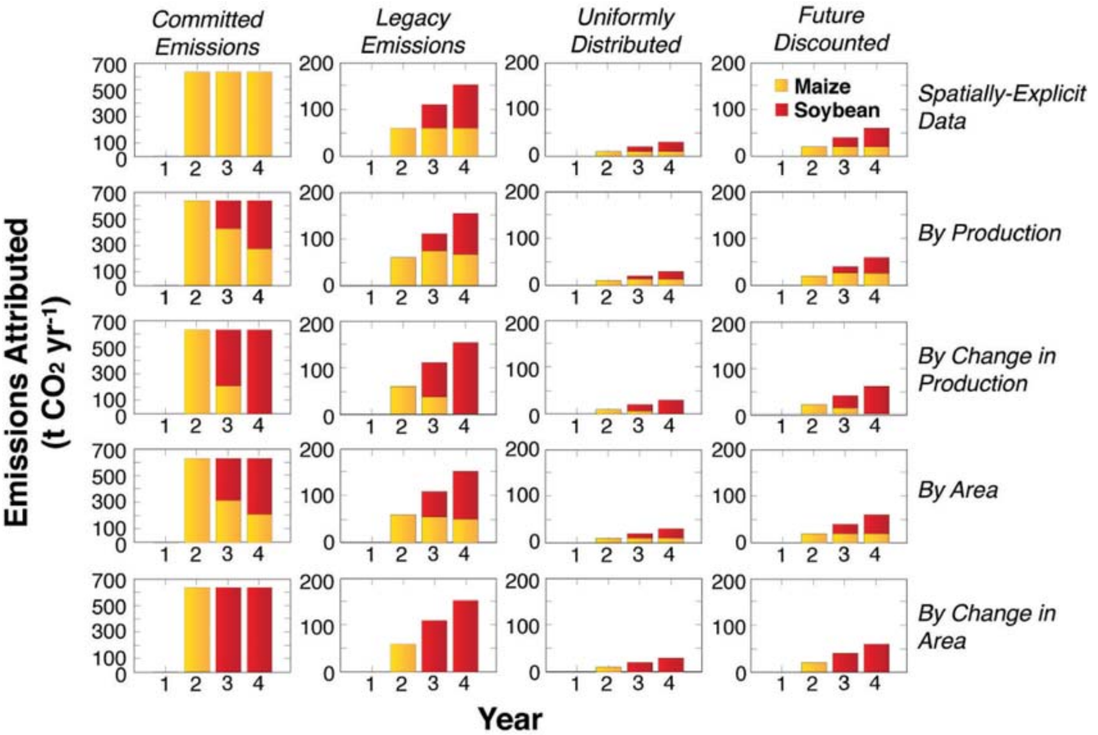

Figure 5. Differences in land-use change emissions attributed to maize (yellow) and soybeans (red) using different accounting methods to distribute the emissions over time (columns) and to the crops (rows). In generating these results, we assume land-use change emissions per hectare of converted forest are distributed as shown in Figure 3B, D & F, and a 4 ha area was converted and used as shown in Figure 4A. Herein, we show only the emissions attributed to products in the 4 years illustrated in Figure 4. With no further land-use change, in year 40, emissions in the 'uniformly distributed' column will be the same while the other columns would be very small. Note that the vertical axis of column 1 differs from that in the other columns in order to accommodate the much larger committed emissions. Different methods lead to very different attributed emissions.

by us humans for our own use and not natural laws to be discovered. Accounting methods are tools to be used for specific purposes. Given this fact, what is important is that analysts conducting carbon accounting of land-use emissions carefully consider the strengths and weaknesses of each approach for their particular purpose and clearly explain and justify their choices. Once an accounting method is chosen, however, calculated values should depend on ascertainable facts.

Future perspective

Irrespective of method, structured and comprehensive accounting of land-use emissions must continue if we are to fully understand global trends in land use and inform policies that effectively maximize agricultural productivity and minimize environmental harms such as land-use emissions. In the coming decade, we expect large advancements in the attribution of land-use emissions, and environmental harms generally, to specific human actions and products. The drivers of this progress we foresee are increasing quantities, types and quality of data on land use and related GHG emissions; increasing interdisciplinarity of analysts, allowing research that relies upon a mixture of methods developed in different and previously unrelated fields such as life cycle analysis, economics and environmental science; and increasing demand for such research as population and affluence of nations grow and environmental resources such as land become even more scarce.

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Executive summary

Background

- Land-use emissions to the atmosphere are predominantly CO_2 from burned or decaying biomass in cleared forest, grasslands or agricultural areas; N_2O from soils amended with organic or synthetic fertilizers; and CH_4 from enteric fermentation in livestock and bacterial methanogenesis of organic matter in anaerobic environments.
- Offsetting land-use emissions to the atmosphere, growing forests and recovering landscapes take up CO_2 from the atmosphere.
- Globally, in recent years, estimates of net land-use emissions are ~1.1 Gt C year^{-1}.

Aim and scope

- Research is increasingly focused on attributing land-use emissions to specific human activities and products, using a wide-range of methods and with different goals.
- This aim of this review is to help analysts by presenting and assessing different methodological options for such research, considering available data and some of the different goals of such accounting.

Land-use emissions

- Land-use emissions include both emissions from land-use activities and emissions from changes in land use. Key sources of land-use emissions thus include N_2O emissions from the application of fertilizers, CH_4 from enteric fermentation in livestock, manure management, and rice cultivation, CO_2 from burning of agricultural wastes as well as logging, wood harvest, and conversion of unmanaged landscapes to human uses.

Distributing land-use emissions in space

- Methods available for attributing land-use emissions to specific geographical regions will depend predominantly on available data and whether biomass products are transported.

Distributing land-use emissions in time

- Four methods available for attributing land-use emissions, and especially land-use change emissions, in time are: (1) All future emissions from a change in land use may be assigned to the year of the change (‘committed’ emissions); (2) The emissions occurring in each year due to past changes in land use may be estimated (‘legacy’ emissions); (3) Committed emissions may be amortized over an arbitrary period of time (‘uniformly distributed’ emissions); or (4) Committed emissions may be distributed by applying a net present value concept (‘future discounted’ emissions).
- Each of these methods may be preferred depending on the purpose of the emissions accounting.

Attributing land-use emissions to actions/products

- After land-use emissions have been assigned to a place and a time, they may attributed to specific actions or products: (1) by the quantities of such goods produced (or actions taken); (2) by the change in the quantity of goods produced (or actions taken) since the previous accounting period; (3) by the area dedicated to the production of the goods; or (4) by the change in the area dedicated to the production of the goods since the previous reporting period.
- Each of these methods may be preferred depending on the purpose of the emissions accounting.

Other issues in attributing land-use emissions

- Contentious issues such as indirect land-use change, permanence and emissions embodied in trade may complicate attributions of land-use emissions. For this reason, these issues are areas of active research.

Conclusions

- To illustrate the large effect the various methods discussed can have on land-use emissions attributed to specific crops, we provide results that apply each combination of methods to the same simple, hypothetical scenario.
- Analysts must consider the strengths and weaknesses of each method for their particular purpose and clearly explain and justify their methodological choices.

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