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Research article

Linking carbon stock change from land-use change to consumption of agricultural products: Alternative perspectives

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A B S T R A C T

Agricultural expansion driven by growing demand has been a key driver for carbon stock change as a consequence of land-use change (CSC-LUC). However, its relative role compared to non-agricultural and non-productive drivers, as well as propagating effects were not clearly addressed. This study contributed to this subject by providing alternative perspectives in addressing these missing links. A method was developed to allocate historical CSC-LUC to agricultural expansions by land classes (products), trade, and end use. The analysis for 1995–2010 leads to three key trends: (i) agricultural land degradation and abandonment is found to be a major (albeit indirect) driver for CSC-LUC, (ii) CSC-LUC is spurred by the growth of cross-border trade, (iii) non-food use (excluding liquid biofuels) has emerged as a significant contributor of CSC-LUC in the 2000's. In addition, the study demonstrated that exact values of CSC-LUC at a single spatio-temporal point may change significantly with different methodological settings. For example, CSC-LUC allocated to 'permanent oil crops' changed from 0.53 Pg C (billion tonne C) of carbon stock gain to 0.11 Pg C of carbon stock loss when spatial boundaries were changed from global to regional. Instead of comparing exact values for accounting purpose, key messages for policymaking were drawn from the main trends. Firstly, climate change mitigation efforts pursued through a territorial perspective may ignore indirect effects elsewhere triggered through trade linkages. Policies targeting specific commodities or types of consumption are also unable to quantitatively address indirect CSC-LUC effects because the quantification changes with different arbitrary methodological settings. Instead, it is recommended that mobilising non-productive or under-utilised lands for productive use should be targeted as a key solution to avoid direct and indirect CSC-LUC.

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1. Introduction

Over the past decades, carbon stock change as a consequence of land-use change (CSC-LUC) has contributed significantly to annual global anthropogenic CO_2 emissions, amounted to 8–20% as a result of deforestation, forest degradation and peat emissions (van der Werf et al., 2009). A major driver is the rapid agricultural expansion driven by both growing domestic and international demand for agricultural commodities (DeFries et al., 2010). A number of studies have sought to assess the relative magnitude of historical CSC-LUC triggered by consumption by quantitatively allocating land-use change (LUC) or CSC-LUC to consumers via bilateral international trade linkages (e.g. Karstensen et al., 2013; Persson et al., 2014; Saikku et al., 2012).

Most of these consumption-based studies, however, do not clearly distinguish between the impacts caused by agricultural expansion and non-productive drivers (i.e. causes of CSC-LUC not yielding tradable agricultural products, such as uncontrolled fire and land abandonment). This is despite evidence showing that non-productive drivers have played important roles in global CSC-LUC (Hosonuma et al., 2012). For example, improper land use practices that have caused uncontrolled fires in Indonesia are among the main reasons for massive CSC-LUC (van der Werf et al., 2008). The non-productive drivers may also indirectly exacerbate deforestation rate, as degradation and loss of arable land potentially drives further agricultural expansion elsewhere to fill the

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production gap. For example, in Brazil, pasture degradation due to inefficient land use followed by land abandonment has driven further pasture expansion into forests (Spera et al., 2014). Thus, not accounting for non-productive drivers and allocating CSC-LUC solely to consumption likely leads to an over-estimation of the impact caused by increasing demand and masks underlying poor land use practices. Recognising and quantifying the magnitude of non-productive drivers helps to identify the underlying causes of CSC-LUC on the producer side and allows designing policies that can target the underlying causes more specifically.

Also, bilateral trade analyses used to link historical CSC-LUC to consumers do not account for indirect effects propagating across spatial boundaries. Concerns over indirect land-use change (ILUC) have been raised in the context of increasing demand for bioenergy (e.g. Searchinger et al., 2008). ILUC occurs when existing agricultural land is converted for biofuel production, leading to agriculture expansion elsewhere to fill the demand gap in the global market through market-mediated effects (Wicke et al., 2012). This is also applicable for demand for food crops – a country with growing consumption will drain the global supply and (in)directly drive further agricultural expansion on a global scale, even if it only imports from countries with no large-scale deforestation. For the case of biofuel, various projection methods (e.g. economic equilibrium models) have been employed to address ILUC, but they are in principle not suitable for distinguishing the effect of different drivers of historical CSC-LUC and are typically subject to high uncertainties (De Rosa et al., 2015; Wicke et al., 2012; Verstegen et al., 2015). Some studies have attempted to cover such propagating effect when accounting for historical CSC-LUC, e.g. Persson et al. (2014) have demonstrated a method to account for ILUC effects within a territory, but the study did not cover global propagating effects.

This work aims to quantify historical CSC-LUC linked to consumptions in different regions, in connection to cross-boundary trades of agricultural products and their end markets while also considering non-productive drivers and indirect effects. The idea is to supply alternative perspectives in viewing the drivers of CSC-LUC from both producer and consumer sides by examining the patterns and trends, particularly when the methodological settings are adjusted, instead of emphasizing the exact magnitude for accounting purpose.

2. Materials and methods

This analysis consists of five major steps with three extensions with the workflows shown in Fig. 1. The method was explained by eight key 'functions' (in italic), i.e. sets of methods, algorithms and parameters embedded in methodologies (see also the previous work Goh et al., 2016 for more details). First, the effects of delineation of spatial boundary were taken into account by repeating the analysis with regional and global setting (section 2.1). Then, by determining the Classification of lands and products and considering the inclusion of non-agricultural and non-productive drivers, a spatially aggregated analysis was performed to determine carbon stock change of individual land classes (section 2.2). This was followed by identifying and capturing direct and indirect CSC-LUC through defining the interactions between land and product classes, propagating effects of marginal changes in land and product use, and allocation mechanism and allocation key (section 2.3). The CSC-LUC was then distributed across time based on a pre-defined temporal dynamics (section 2.4). In the last step, a mechanism was proposed for defining the extent of trade linkages so that the calculated CSC-LUC can be allocated to local and distant consumption as well as non-productive drivers (section 2.5). In addition, three extensions were designed for wood products, palm oil and soy-beef chain to further explore the impact of adjusting the setting, i.e. employing different ways to address specific issues related to them (section 2.6–2.8). The data collection and processing was described in Box S1 (supplementary materials), especially the assumptions made to compromise with data shortage. A key assumption is that only living biomass (i.e. above and below ground carbon stock) was accounted, but not soil carbon and dead organic matter due to high data uncertainty (see the last paragraph of Box S1). For comparison, the method was tested with the inclusion of peat emission in section 2.7.

2.1. Examining the effect of changing spatial aggregation

The first step was delineation of spatial boundary, i.e. setting the boundaries between different territories within the study area. The analysis would be repeated with two spatial settings, i.e. on a global and a regional scale, to evaluate the effect of changing spatial aggregation on the results. In the global setting, all lands and forests were treated as global assets, and therefore all consumption regardless of geographical regions share the same liability without trade analysis. This setting aimed to inspect overall trends of CSC-LUC by resolving all indirect effect through aggregating all changes (i.e. only the net changes on global level were inspected). In the regional setting, regions were treated as individual closed territories that were linked via trade. This provided more details on different developments in each region. Table S1 shows the aggregation of spatial boundaries (continental and sub-continental) for the regional setting. The analysis was first performed with a global setting using step 2 to 4, and repeated with a regional setting using step 2 to 5 and three extensions, generating two separate sets of results.

2.2. Determining carbon stock changes of individual land classes

This step aimed to calculate the total carbon stock stored in individual land classes and its changes over time (e.g. how much carbon is stored in the land class 'fruits' in this year compared to

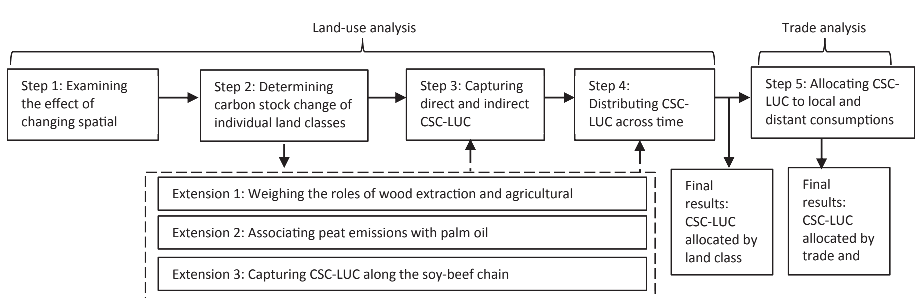

Fig. 1. Work flow of this study to allocate historical CSC-LUC to different drivers.

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