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Estimation of CO_2 emissions in the life cycle of roads through the disruption and restoration of environmental systems

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ABSTRACT

Effects of disruption and restoration of terrestrial ecosystems have been largely overlooked when conducting assessments of greenhouse gas (GHG) emissions in road construction projects. This is an important oversight given the intensive land-conversion generated by linear infrastructure development, as well as the relevance given to carbon pool variations associated with land use and land-use changes by national inventories of GHG emissions and global reports. This paper describes the implementation of a methodology to classify those environmental systems in land-uses categories, to determine their carbon stocks (vegetation and soil), and to quantify CO_2 emissions and removal related to their management at the different stages of road construction projects. The procedure is illustrated through its application in the impact assessment of road projects in the territory of Spain. This methodology integrates currently available information on carbon stocks and considers the accounting criteria adopted in national GHG emissions inventories. It is intended to constitute part of an integral assessment tool for GHG emissions in linear infrastructure projects. Four case studies are presented in which emissions from the disruption of environmental systems range from 0.55 to 3.66 kT CO_2 km^{-1}. This represents 5 to 13% of the total emissions in the construction stage, and 3.5 to 7% of the net CO_2 balance, i.e., once the initial carbon sequestration by restoration planting has been discounted. Results also indicate that under ideal conditions the long-term effect of restoration may even fully offset this impact, though really such conditions are far from being the case in the usual development of plantations. This study confirms the advisability of systematically incorporating the analysis of land use and land-use changes into the assessment of GHG emissions of road projects for consideration in decision-making from the design stage to the maintenance stage in such projects.

Abbreviations: LCA, life cycle assessment; LULUC, land use and land-use change; $\Delta_{50}C_{RP}$, CO_2 budget or accumulated (50 years) change in carbon stocks associated with a road project; $C_{LUA/B}$, carbon density for each land use before/after the construction stage; $\Delta_{50}C_{LUA}$, accumulated (50 years) change in carbon stocks per area unit for each land use after road construction; $S_{LUA/B}$, removed or restored surface, correspondingly, for each land use; CORINE, coordination of information on the environment program; C_{VEG}, vegetation carbon density; C_{SOIL}, soil carbon density; C_{LB}, carbon density in living biomass; C_{DW}, carbon density in dead wood; C_L, carbon density in litter on the ground; C_{SOM}, carbon density in soil organic matter; AB, aboveground biomass; R, root-to-shoot ratio; CF, carbon fraction of dry matter; V, merchantable volume with bark; D, basic wood density; BEF, biomass expansion factor for conversion of merchantable volume with bark to aboveground tree biomass; SOC, concentration of soil organic carbon in a given soil mass; SBD, soil bulk density; Depth, soil depth considered; Δ_1 $C_{tp\ LUA}$, annual change in carbon density for a land use until 20 years after planting (transition period); Δ_1 C_{geLUA}, annual change in carbon density for a land use during the 30 years after the transition period.

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1. Introduction

National GHG emissions inventories (see Baritz and Strich, 2000; Brack et al., 2006; EPA, 2011; Hamilton and Vellen, 1999; MARM, 2009a) explicitly follow the provisions of the Kyoto protocol regarding activities pertaining to natural CO_2 sinks such as forestation, deforestation and other land-use activities, and changes of use and forestry (LULUCF sector) in the evaluation of emissions. Similarly, life cycle assessment (LCA) standards ISO 14040 and ISO 14044 (ISO, 2006a,b) and more specifically, those relating to the quantification of GHG emissions, such as regulation PAS 2050:2008 (BSI et al., 2008), highlight the importance of considering the impact on ecosystems. Nevertheless, useful information about terrestrial ecosystems and their carbon stocks (the carbon stored in vegetation and soil pools) is available in many regions and countries. Furthermore, different methodologies and validated data exist for determining carbon stocks and for calculating CO_2 budgets that result from changes in land use and carbon sequestration in natural sinks (IPCC, 2003; MARM, 2009a); such methodologies and data are implemented in national GHG emissions inventories. In parallel, studies dealing with the determination of carbon stocks considering large-scale spatial variability and long-term dynamics of these stocks are becoming more common in the literature (Dawson and Smith, 2007; Gibbs et al., 2007; Müller-Wenk and Brandão, 2010; Muñoz-Rojas et al., 2011; Ostle et al., 2009).

Notwithstanding the above, some authors (Milà i Canals et al., 2007; Müller-Wenk and Brandão, 2010) recently reported that the GHG effect of land-use change is seldom included in LCA. This discredits LCA results for many stakeholders, and is difficult to justify given that the impact of land-use change amounts to approximately 20% of global emissions (Rogner et al., 2007). In order to address this issue, authors like Milà i Canals et al. (2007) or Schmidinger and Stehfest (2012) have proposed frameworks for land-use impact assessment within LCA. The latter study provided an overview of the different approaches underlying the inclusion of this impact. These approaches range from accounting based on the net area balance between original and resulting types of carbon sinks, to complex carbon exchange models that also include delayed carbon uptakes and missed potential carbon sinks due to land occupation. However, there is as yet no consensus on the method to be applied in LCAs, since the method of choice depends greatly on the accounting approach chosen and on the information available.

The required determination of carbon stock changes and CO_2 budgets in regards to land use and land-use change (LULUC) heavily depends on both adequately categorizing environmental systems and characterizing the resultant land-use categories. Then, first, a balance between accuracy and operability should be considered in the development of categorization criteria. In the case of Spain, a land-use categorization of reference is available (MARM, 2009b), but requires adaptation in order to assess carbon sinks. Second, the characterization of land-use categories involves the determination of their carbon stocks in both vegetation and soil, based on the knowledge of each of their significant carbon pools (IPCC, 2003). Moreover, in addition to the initial carbon stock changes produced during the implementation of the road project, the potential CO_2 sequestration in the long-term by new land uses ensuing from restoration also becomes relevant when analyzing carbon footprint throughout the road life cycle (Bouchard et al., 2013; Madej et al., 2013) and should be considered in the methodological development.

Allocation of emissions to the different stakeholders is also relevant when tackling the issue of global warming impact, either because of regulations or at least due to the implications of corporate social responsibility. But it is the fact that no directive for assigning responsibility for CO_2 flows related to LULUC is found in the main corporate standards for emission accounting and report such as the GHG Protocol for organizations (WBCSD and WRI, 2004), the PAS 2060 (BSI, 2010) or ISO 14064 (ISO, 2006c). Therefore, the definition of criteria for the allocation of these emissions is needed.

In particular, an extensive review of studies evaluating GHG emissions in the life cycle of roads (Cass and Mukherjee, 2011; FNRA, 1999; Gerilla et al., 2000; Huang et al., 2009; Park et al., 2003; SUSCON, 2006) confirms that the contribution made by land-use change is nearly disregarded, although the magnitude of the land-conversion impact from road construction is evident. Indeed, the earliest carbon footprint study of an entire road project (Stripple, 2001) already reported a remarkable, although roughly estimated, contribution of forest felling to the construction stage emissions. In this context, our hypothesis is that the impact of environmental system destruction by construction works on carbon stocks would represent a significant component of the CO_2 balance of road projects. Furthermore, we foresee that short-term and long-term effects of restoration may substantially offset the impacts generated. In this line, we have converged with the very recent work of Melanta et al. (2013), the only study to address these issues rigorously.

From the foregoing, we understand that LULUC effects on carbon sinks should necessarily be incorporated into any tool for the integral analysis of GHG emissions of road projects. The management information system called CO_2NSTRUCT (Barandica et al., 2013) is a tool intended to assist in the management of road projects from the initial phases of design and analysis of alternatives, providing a comprehensive assessment of its global warming impact. Its results should support the decision-making process when comparing among alternative road layouts, project designs, restoration options or specific interventions involving soils and vegetation (e.g., disposal or reuse). By developing and implementing in CO_2NSTRUCT an operative methodology for assessing LULUC effects, we aim to complete the scope of most of the previous models. Moreover, the exhaustiveness of the analysis of this tool, which includes all the emission components and phases of road projects, provides the proper context for adequately evaluating the contribution of any component to the road carbon footprint in relative and comparative terms. This and the possibility of allocating the emissions amongst the responsible actors are distinguishing features of CO_2NSTRUCT compared to the existing models, including the abovementioned model presented by Melanta et al.

In this paper, we attempt to implement the analysis of the CO_2 budget (net balance of CO_2 emissions and captures) resulting from the LULUC associated with the construction and use-maintenance stages of roads. The aim is to establish an estimate of the magnitude of this CO_2 exchange and to evaluate the relative significance of its contribution to the total GHG balance of a road project throughout its life cycle. The specific objectives involve, first, determining the carbon stocks of vegetation and soil and quantifying their oxidization associated with the elimination of environmental systems on the lands affected (temporarily or permanently) by road construction or maintenance works. Second, we aim to determine the CO_2 captures as a result of either the replacement or substitution of those systems in recoverable zones, in addition to the development of the restoration plantings throughout the road's service life. Third, we are involved in proposing reasoned criteria for allocating the responsibility for the LULUC-related emissions in road construction projects. The applicability of this approach will be tested using case studies of road development projects in Spain.