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Methodological uncertainties in estimating carbon storage in temperate forests and grasslands

Océane Bartholomée*, Karl Grigulis, Marie-Pascale Colace, Cindy Arnoldi, Sandra Lavorel

Laboratoire d'Ecologie Alpine, LECA, UMR UGA-USMB-CNRS 5553, Université Grenoble Alpes, CS 40700, 38058 Grenoble Cedex 9, France

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ABSTRACT

Carbon sequestration is an essential ecosystem service (ES) for climate change mitigation. For reasons of simplicity this ES is often quantified considering carbon storage in four carbon pools: aboveground biomass, belowground biomass, dead organic matter and soil organic carbon. Indicators of these four pools are estimated by modelling, reference values, or field methods and data processing of different complexity levels which requires comparing estimations. In order to facilitate the assessment of carbon pools, e.g. in environmental impact assessment, a fast, reliable and easily applicable method is required. First, using a systematic literature review we identified frequently used field methods for estimating carbon pools for forests and grasslands, two ecosystems playing a key role in global climate regulation. Second, from this review we developed field methods for indicators of each carbon pool – aboveground biomass, belowground biomass, soil organic carbon and dead organic matter – in both ecosystem types. We applied these methods in a set of forest and grassland plots in the Grenoble region (France) and asked i) how comparable and consistent are alternative methods for each carbon pool? ii) what is the variability of estimates between these methods? and iii) which level of simplicity has an acceptable level of uncertainty? Thereby, we conducted for the first time method comparisons for all four carbon pools. We based our method comparisons on the quality of the linear relationships between methods and their level of accuracy relatively to the chosen reference methods (the method assumed to be the closest to the actual carbon stock). For most carbon pools – e.g. aboveground biomass and soil organic carbon, both major carbon stocks – selected alternative methods were comparable and consistent with the reference method. Third, we built on these results to suggest easy and quick field methods for each carbon pool in each ecosystem type with accuracy levels between 10 and 20%. We provide guidelines together with associated uncertainty levels to scientists and practitioners aiming to estimate the ecosystem service of global climate regulation from carbon stocks in terrestrial ecosystems. The guidelines also allow adjusting method selection to human, knowledge and financial resources available in the study context.

1. Introduction

In the face of accelerating climate change (Smith et al., 2015) and of its observed and projected impacts on ecosystems and biodiversity (Scheffers et al., 2016), global climate regulation by ecosystems is an essential ecosystem service to society (Díaz et al., 2018). Quantifying terrestrial, aquatic and marine ecosystems ability to reduce atmospheric greenhouse gases concentrations is therefore essential, especially if international political and economic mechanisms for regulating carbon emissions and sequestration are to be operational (Díaz et al., 2018). Carbon sequestration in ecosystems supports the essential ecosystem service (ES) of climate regulation which benefits to human well-being at global scale (MEA, 2005) and is one of Nature's eighteen essential Contributions to People (Díaz et al., 2018). The global climate regulation service is a regulating ecosystem service mitigating climate change induced by anthropogenic emissions, and is mainly supported by plant photosynthesis and the activity of soil microorganisms (Dignac et al., 2017). Given international accounting and trading mechanisms, this ES is often estimated by monetary valuation (Luisetti et al., 2013; Tardieu et al., 2013). Economic (or instrumental), and specifically monetary valuation, is one of the values that can be attributed to an ES, but is only one of the three pillars of integrated valuation which also includes biophysical (or intrinsic) and social (or relational) values (Jacobs et al., 2018; Pascual et al., 2017).

To quantify the biophysical value of global climate regulation carbon sequestration is commonly quantified by measuring or

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* Corresponding author.
E-mail address: oceane.bartholomee@univ-grenoble-alpes.fr (O. Bartholomée).

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estimating carbon fluxes between the atmosphere and ecosystems. Its direct measurement requires significant equipment (flux towers (Gilmanov et al., 2006); eddy covariance systems (Sándor et al., 2016)), resources, and knowledge. Alternatively, it is often estimated through the measurement or modeling of ecosystem carbon fixation, or calculated as the difference of carbon stocks, the carbon actually stored in ecosystems, between two dates. Carbon storage is thus a proxy often used to simplify the estimation of the ecosystem service of global climate regulation. Carbon storage is the amount of carbon present in one or more carbon pools of an ecosystem at a specific time. However, care should be taken as carbon stock estimation is a rough proxy for climate regulation which does not reflect the variations of carbon flux speed, another consequence of climate change (Ziegler et al., 2017). For a more comprehensive estimation of the ES of global climate regulation, carbon stock estimation should be combined with flux measurements.

The estimation of terrestrial carbon storage usually considers four carbon pools. First aboveground biomass (AGB) includes aboveground parts of trees (stem, branches, and leaves), shrubs and herbaceous plants. The belowground biomass pool (BGB) covers coarse and thin tree roots but also shrub and herbaceous roots. The dead organic matter pool (DOM) includes dead organic matter on the soil surface as well as litter and dead wood. Lastly the soil organic carbon pool (SOC) is considered across soil layers. These carbon pools are used for field estimation of carbon storage using dedicated indicators in tools for practitioners such as the Toolkit for Ecosystem Service Site-based Assessment (TESSA) (Peh et al., 2013). They are also often used for modeling the global climate regulation service, for instance in the free and open source ES model InVEST (www.naturalcapitalproject.org), which has been applied to Mediterranean forest (Bottalico et al., 2016), tropical forest in Brazil (Chaplin-Kramer et al., 2015), and across different land cover types of the Spanish Basque Country (Palacios-Agundez et al., 2015).

Different methods are available for estimating each of the four carbon pools. These include modeling, field measurements coupled with potential laboratory and mathematical analyses, and use of values from literature reviews. For instance for AGB, carbon storage can be estimated using forest growth models (e.g. CenW, (Dymond et al., 2012)), tree measurements in the field coupled with allometric equations (Conti and Díaz, 2013), or through data analysis from national forest inventories or forest studies (Cademus et al., 2014; Poorter et al., 2016). For SOC, carbon storage can be estimated using a soil carbon model (Bandaranayake et al., 2003), the IPCC (Intergovernemental Panel on Climate Change) standard value (Zandersen et al., 2016) or using direct field measurements (Preger et al., 2010).

At local scales there is increasing demand for the inclusion of ecosystem services in environmental impact assessment and land planning (Albert et al., 2016; Diehl et al., 2016). This requires the development of easily applicable, consensus methods that enable comparability between studies and some consistency across carbon storage estimates. In addition, there is a need to assess uncertainties associated with common methods for quantifying the four carbon pools, so that different methods of varying complexity applied in different studies may be compared.

In this study, we assessed methodological uncertainties associated with methods for field measurement of indicators of each carbon pool. Rather than identifying the ”best” universal method, we aimed to provide an assessment of existing methods to help guide researchers and practitioners in method selection and highlight their associated risks. Specifically, we asked: i) how comparable and consistent are the different methods for each carbon pool?, ii) what is the variability of estimates between these methods?, iii) which level of simplicity has an acceptable level of uncertainty?

To answer these questions we first identified existing methods for each carbon pool based on a systematic literature review. Second we assessed field protocols for both tree-dominated and grass-dominated ecosystems. Forest ecosystems store significant carbon in their AGB pool under temperate, tropical and boreal climatic conditions (Bonan, 2008). The importance of grassland ecosystems for carbon storage, especially in their soil pools has also been repeatedly emphasized (Lal, 2004; Minasny et al., 2017). Protocols were tested in the Grenoble region (France), which comprises a broad range of temperate forest and grassland ecosystems. Third, we compared the carbon stock estimations measured with the different field methods to the selected reference method, providing a first comprehensive comparison of field methods for the four major carbon pools. Based on the analysis of these results we discuss for each carbon pool the relative merits of the methods in balancing simplicity and/or rapidity, and the reduction of uncertainty. We expected estimation methods of major and well-studied carbon pools – i.e. forest AGB and SOC – to be more numerous and more easily simplified thanks to greater knowledge of their characteristics and functioning and to abundant data. Conversely, for overlooked carbon pools such as BGB and dead organic matter, we supposed that fewer methods would be available and that they would be less accurate due to both fundamental knowledge and data gaps.

2. Methods

2.1. Literature review

We reviewed the literature to determine the current range of indicators and methods used to estimate carbon storage. *ISI Web of Knowledge* was searched in a three stage process using sets of key-words for which all results were systematically checked between 20/03/2016 and 13/04/2016. The first step focused on carbon sequestration/storage modeling to identify variables considered for this service. The second step focused on literature specific to ecosystem services and the underlying ecological functions/processes to find field methods for estimating carbon sequestration/storage. The third step broadened the search to ecological literature not referring explicitly to the ecosystem service concept and dealing with carbon storage estimation in the field. Ultimately, focusing on modeling was sufficient, as these sets of keywords produced 360 papers addressing carbon storage modeling, biophysical measures and their combination, with biophysical measures being used for the model calibration (Table A1 in Appendix A).

A first selection of paper titles and abstracts yielded 243 papers. Papers were discarded if carbon sequestration or storage was not estimated explicitly or was considered only from an economic perspective. A second selection was done after reading the methods section. Papers which did not detail the model or method used were discarded, leaving 157 papers for detailed analysis (Appendix B). A synthetic table was filled with information from the selected papers (Table A2 in Appendix A). The Methods sections of the selected papers were reviewed. The more common indicators and field methods for each carbon pool were retained and considered in depth in order to be tested in the field as presented below.

2.2. Study area

The urban area of Grenoble (45°11′ N/5°43′ E) is a basin surrounded by three mountain ranges: Belledonne, Chartreuse, and Vercors. It also comprises plateaus and valleys, and is shaped by the confluence of three rivers: the Isère, the Drac and the Romanche, supporting fertile floodplains with arable lands and numerous wetlands (Vannier et al., 2016). Overall, this richness of physical and natural features shapes a high diversity and heterogeneity of landscapes which allowed us to work on a wide range of ecosystems, representative of variation in similar temperate regions. This study focused on an array of typical forest (10 sites: 4 on valley moraine soil, 3 on alluvial soil and 3 forests on slopes) and grasslands (11 grassland plots: 8 humid grasslands for AGB of which 3 were considered for SOC -, and 3 mesophilic grasslands) (Table C1 in Appendix C). All sites were located within the regional ecological corridors network, or within the regional “Sensitive Natural Areas”