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What crop type for atmospheric carbon sequestration: Results from a global data analysis

Isack Mathew[a], Hussein Shimelis[a], Macdex Mutema[a], Vincent Chaplot[a,b,*]

[a] University of Kwa-Zulu Natal, School of Agricultural, Earth & Environmental Sciences, Scottsville, 3209 Pietermaritzburg, South Africa
[b] Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques (LOCEAN), UMR 7159, IRD/C NRS/UPMC/MNHN, IPSL, 4, Place Jussieu, 75252 Paris, France

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ABSTRACT

Sequestration of atmospheric carbon (C) into soils is a strategy to compensate for anthropogenic emissions of carbon dioxide. The response of SOCs to crop types is yet to be determined under different environments. The objectives of this study were to elucidate the impact of crop type on the allocation of atmospheric C to shoots and roots, and ultimately to the soils and to determine its association with soil carbon stocks. Three hundred and eighty-nine field trials were compared to determine allocation of biomass and C in plants and SOCs under fields of different crop types. Grasses had the highest plant biomass production (19.80 ± 1.16 Mg ha^{-1} yr^{-1}), followed by cereals (9.44 ± 0.45 Mg ha^{-1} yr^{-1}), fibre (7.90 ± 1.00 Mg ha^{-1} yr^{-1}), legumes (3.29 ± 0.63 Mg ha^{-1} yr^{-1}), and oil crops (3.05 ± 1.16 Mg ha^{-1} yr^{-1}) showing significant differences ($p < 0.05$). Maize (6.3 ± 0.34 Mg C ha^{-1} yr^{-1}) had the highest plant C amongst summer crops, while wheat (2.2 ± 0.35 Mg C ha^{-1} yr^{-1}) had the highest plant C amongst winter crops. In all the studies, crops allocated more C to their shoots than roots yielding root C: shoot C (Rc/Sc) ratios below magnitude. The greatest C allocation to roots was in grasses (Rc/Sc = 1.19 ± 0.08), followed by cereals (0.95 ± 0.03), legumes (0.86 ± 0.04), oil crops (0.85 ± 0.08), and fibre crops (0.50 ± 0.07). There was evidence that high plant C stocks were found in crops grown under carbon rich clayey soils of tropical humid areas. Natural grasses and cereals should be promoted as they appeared to yield greater potential for atmospheric carbon sequestration in plants and soils. Overall, the study evaluated the relative potential of the main crop types to sequester atmospheric C useful in screening of crop types for carbon efficiency and for development of plant C models.

1. Introduction

Land-use is a key determinant of soil carbon stocks (Bolin et al., 2000). Any change in land-use affects the flow of soil carbon (C) until a new equilibrium is eventually reached under the new land use conditions. Each soil has its own C-carrying capacity (i.e. an equilibrium C content) dependent on the nature of vegetation, soil type and climate (Gupta and Rao, 1994; Lal, 2004a). Soil carbon stocks (SOCs) under a certain vegetation type are a result of a balance between C inflows and outflows (Fearnside and Barbosa, 1998). Land-use change and land mismanagement, which started several thousands of years ago, have dramatically depleted SOCs with most, if not all, of the carbon lost from soils having been emitted to the atmosphere with an estimated 3.5C Pg annual increase in atmospheric C (Albrecht and Kandji, 2003). Lal (2004b) estimated that soils around the world have lost between 25 and 75% of their C stocks with a cumulative 78 billion tons of C having been lost due to soil degradation, changes in vegetation and tillage operations, among other factors. For instance, several studies investigating the impact of land use conversion from native forests or grasslands to croplands pointed to a dramatic depletion of soil carbon stocks (Conant et al., 2001; Guo and Gifford, 2002).

Guo and Gifford (2002), using a meta-analysis based on data from 74 publications, indicated that SOCs declined by an average of 42% from native forest to cropland and by 59% from grassland to cropland. During this process, soil acted as a C source while the atmosphere acted as the sink. However, this process is largely reversible with part of the C lost from soils being potentially stored back to the soils. Land use change has already demonstrated this potential because changing from cropland to pastures and secondary forests have increased SOCs by 19 and 53%, respectively (Guo and Gifford, 2002). In addition to C sequestration, several land-use options that increase organic matter and tighten the soil nitrogen (N) cycle can yield powerful synergies,

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[*] Corresponding author at: University of KwaZulu-Natal, School of Agricultural, Earth & Environmental Sciences, Rabie Saunders Building, Scottsville 3209, Pietermaritzburg, South Africa.

E-mail address: vincent.chaplot@ird.fr (V. Chaplot).

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such as enhanced fertility and productivity, increased soil biodiversity, reduced erosion, and runoff and water pollution (Paustian et al., 2016). Although strategies involving land use conversions from crop production to pasture or forestry have huge potential to increase SOCs, they are in direct conflict with crop production which seeks to increase global food security. There were also suggestions that native grasslands may be close to attaining soil C equilibrium (Cole, 1996) and therefore focusing on restoration of soil carbon stocks in degraded agricultural lands, which are below soil C equilibrium, presents higher potential to sequester atmospheric C.

Plant C is important in the global C cycle because annually more than 10% of all atmospheric CO_2 passes through the plant-soil-atmosphere interface (Raich and Potter, 1995). Therefore, fostering the ability of plants to fix atmospheric CO_2 presents a huge potential to reduce atmospheric C concentration. To our knowledge, there are many studies focusing on tillage impacts on SOCs but there are a few which investigated the quantitative relationship between plant C and SOCs. Balesdent and Balabane (1996) reported that root derived C accounts for between 60 and 75% of SOCs showing that root biomass and C are important determinants of SOCs. Most studies that investigated C allocation patterns in plants reported that grasses accumulate higher amounts of C than crops. The variations in plant C allocations suggest that there could be significant differences in plant C allocation across crop types, climatic zones, and soil types. The differences are certainly critical in the eventual deposition of plant C into soil C pools and can be used to select crop varieties with superior C sequestration potential. Therefore, it is important to understand the C input of different parts (root vs shoot) in order to strategize options that aim at increasing SOCs (Rasse et al., 2005). The disparities in land management practices, crop types and environmental conditions make it difficult to compare carbon sequestration potential of the different main crops. However, data from various studies across the world can provide an opportunity for comprehensive analysis seeking to draw general understanding on the allocation of carbon to shoots and roots and the correlations between plant C and soil C. The data need to be integrated over time, space and climate through focused data analysis and interpretation for wider application. Therefore, the objectives of this paper were to integrate results from different studies worldwide in order to evaluate differences in root and shoot biomass, and C stocks of the main crops and then to deduce the extent to which the stocks correlated to soil C under different environmental conditions. Information on the differences in biomass and carbon allocation and their relationship with SOCs is useful to estimate the relative potential of the main crops to sequester atmospheric C and enable preliminary screening of crop varieties for carbon efficiency. The determination of C allocation between shoots and roots reflects the differential investment of C between the two parts and it was hypothesized that production of crops with high root C investment may improve SOCs.

2. Materials and methods

2.1. Study setup

The study is based on data collected mostly from field experiments conducted under various standard farming practices. Literature search was conducted on electronic academic databases using search engines such as Google Scholar, Refseek, Science Direct, SciFinder, Scopus, Springer Link and Web of Science. Key words such as carbon allocation; carbon partition; root: shoot biomass carbon; plant carbon sequestration; rhizodeposition and plant/soil organic C stocks were used to search for journal articles published from 1990 to time of the literature search in early 2016.

In order to be included in the analysis, studies had to report on root and shoot biomass, root and shoot C concentration or stocks, and soil organic C stocks (SOCs) measured during the experimental periods. In some papers, these variables were derived from root: shoot ratios, harvest indices, soil organic C concentration or referred publications on the same experiment. Data based on crop rotation systems where C changes were reported for one crop were only used on a limited scale. In order for data from crop rotations to be included, the researchers had to differentiate the contributions from the individual crops in the systems. Each year in a multiple year experiment was treated as a separate and independent trial, while a mean was computed for each treatment in the case of replicated values.

Information regarding geographical location, long-term climate conditions, soil properties, and duration of the experiments was also collected. Details of land and crop management practices such as tillage, water regimes and crop rotations were considered to be optional. A total of 42 journal articles (Table 1) detailing different studies across the world were obtained using the above criteria and this provided 389 observations. Names of authors, year of paper publication, geographical location of experimental site, nature of experiment, crop type(s) used in the experiments, quantitative information on plant biomass, C variables and environmental conditions were captured onto a database (S1). Long-term climate variables (such as MAP: mean annual precipitation and MAT: mean annual temperature), soil properties (including pH, texture and bulk density) and tillage operations were used to stratify the observations in the database. However, tillage operations were not used in the actual analyses. These environmental factors influence SOCs and plant C through their effects on crop productivity, microbial activity and soil properties.

2.2. Definitions of environmental factors, and plant and C variables

2.2.1. Environmental factors

This analysis considered the following environmental factors long-term mean annual precipitation (MAP) and mean annual temperature (MAT), geographical location as defined by coordinates (LAT: latitude and LON: longitude) and soil properties (clay content, bulk density and pH) (Table 3). Although data on type of tillage was collected as a means for identifying the different soil management practices, this information was not used in the final analysis because several studies already investigated the impact of tillage on C sequestration (e.g. Abdalla et al., 2015; de Moraes Sa et al., 2014; Ghosh et al., 2006; Sainju et al., 2005). In the cases where MAP and MAT were not provided in the papers, the data were obtained from Climate (2016) using the location coordinates (LAT and LON). Climate is further categorized into tropical (hot and wet), subtropical (warm and arid to humid) and temperate (cold and arid to moist) according to MAP and MAT. Soil texture was derived from the journal articles and categorized following Mutema et al. (2015). Soil bulk density (BD) was cited from the articles and where BD was given for different horizons, the average for the whole profile was calculated. Soil pH (acidity or alkalinity) used in the current paper is based on $CaCl_2$ scale averaged across the soil profile. The water based pH was converted to $CaCl_2$ pH scale following Lierop (1981):

$$y = 0.53 + 0.98x \quad (1)$$

Where y is the water based pH and x is pH on the $CaCl_2$ scale.

2.2.2. Biomass variables

All definitions adopted in the paper are strictly for purposes of the current analysis and are not for universal application. Natural grass refers to native and/or pasture grasses which are distinctly different from cereal crops; and for simplicity are referred as grass. Plant biomass refers to total plant mass (root and shoots) but excluding grain biomass in cereals and legumes or lint in cotton. Total plant biomass including reproductive parts was considered in grass because there was no clear distinction between harvestable forage and residual biomass. Shoot biomass was defined as total above ground biomass (leaves and stems) excluding grain, lint or pods. Root biomass referred to all biomass found below the soil surface (crown roots, rhizomes and nodules) excluding