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Carbon uptake by European agricultural land is variable, and in many regions could be increased: Evidence from remote sensing, yield statistics and models of potential productivity

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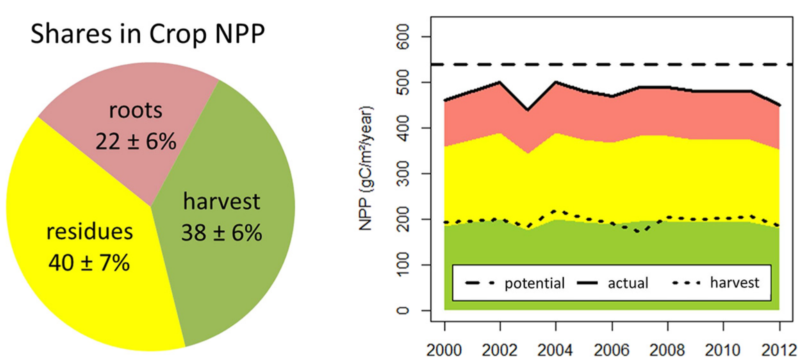
HIGHLIGHTS

- We provide robust consistent carbon uptake information for agricultural lands.
- European agriculture exhibits a yield gap of 10%, in particular in the south and east
- Agricultural plants allocate about 40% of carbon into aboveground harvestable parts.
- In Europe crops have a higher carbon uptake than forests (409 vs. 292 Mt C per year).

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural plants, covering large parts of the global land surface and important for the livelihoods of people worldwide, fix carbon dioxide seasonally via photosynthesis. The carbon allocation of crops, however, remains relatively understudied compared to, for example, forests. For comprehensive consistent resource assessments or climate change impact studies large-scale reliable vegetation information is needed. Here, we demonstrate how robust data on carbon uptake in croplands can be obtained by combining multiple sources to enhance the reliability of estimates. Using yield statistics, a remote-sensing based productivity algorithm and climate-sensitive potential productivity, we mapped the potential to increase crop productivity and compared consistent carbon uptake information of agricultural land with forests. The productivity gap in Europe is higher in Eastern and Southern than in Central-Western countries. At continental scale, European agriculture shows a greater carbon uptake in harvestable compartments than forests (agriculture 1.96 vs. forests 1.76 t C ha^{-1} year^{-1}). Mapping productivity gaps allows efforts to enhance crop production to be prioritized by, for example, improved crop cultivars, nutrient management or pest control. The concepts and methods for quantifying carbon uptake used in this study are applicable worldwide and allow forests and agriculture to be included in future carbon uptake assessments.

1. Introduction

Cropland occupies 11.7% of the world's land surface, with 80% of this area rain-fed and 20% irrigated (FAO, 2011). The importance of

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agriculture to the global carbon (C) cycle is well recognized. Direct emissions from the agriculture, forestry and other land use (AFOLU) sector account for 24% of anthropogenic greenhouse gas emissions in 2010 (Smith et al., 2014; Tubiello et al., 2013). Other non-greenhouse-gas-mediated effects such as albedo changes due to AFOLU also affect climate (Kirschbaum et al., 2013). Agriculture, therefore, substantially affects our climate and the global C balance (Bondeau et al., 2007; Ciais et al., 2010; Monfreda et al., 2008; Smith, 2004; Smith et al., 2008).

Although a large number of models for estimating crop production exist, such models often only capture agriculture, or only certain crop types (Elliott et al., 2015; Palosuo et al., 2011), often cannot provide temporal-continuous information or operate at coarse spatial resolution (Ciais et al., 2010). Such restrictions limit our ability to quantify C uptake by vegetation accounting for small-scale variation of soil fertility, fragmentation of land use, management patterns, disturbances etc.

C absorbed via photosynthesis is stored in carbohydrates and the total assimilated C is the Gross Primary Production (GPP). About half of GPP is soon released to the atmosphere via autotrophic respiration (Zhao et al., 2005). The remaining part, the Net Primary Production (NPP), is allocated into compartments with a longer residence time such as leaves, roots or other structures (Scurlock and Olson, 2002). About two thirds of NPP is allocated into fine roots and litterfall, both exhibiting a high turnover rate and low residence time (Malhi et al., 2011; Zhang et al., 2008). The rest is allocated into plant biomass (stem, coarse roots, leaves, fruits, grains or tubers) and, depending on the land management, is consumed by humans and animals for food or fiber, is used for bioenergy, or left in the field where it decomposes, with a small fraction remaining in longer-lived pools in soil organic matter (Smith et al., 2010).

Net Primary Production can be directly measured by quantifying its compartments (allocation into biomass, above- and belowground turnover), yet there are few measurements available (Scurlock and Olson, 2002). Models can utilize this scarce but highly valuable information. Using a single consistent model, that can deliver information of C uptake by forests, croplands and other land cover types such as savannahs and shrublands, would avoid biases arising from input data and cross-border effects by sampling or modelling concept. Remote sensing data may be useful for crop monitoring and forecasting of yield (de Wit and van Diepen, 2008). A model using satellite remote sensing information and capturing all land cover types worldwide is MOD17, which provides productivity information since the year 2000 at 1-km resolution (Zhao et al., 2005; Zhao and Running, 2010). MOD17 combines a biogeochemical model framework with satellite-based, remotely-sensed vegetation information, derived from the MODIS sensor (MODerate-resolution Imaging Spectroradiometer) on board the TERRA and AQUA satellites, operated by the National Aeronautics and Space Administration (NASA) of the United States of America. Since MOD17 NPP was validated for croplands with data from only site in North America (Turner et al., 2006, 2005), evaluation with large-scale European crop statistics may enhance our knowledge on the reliability of MOD17 outputs.

Running MOD17 with high-resolution European climate data (E-OBS) resulted in an improved regional NPP dataset (MODIS EURO) (Neumann et al., 2016b). MODIS EURO has already been shown to capture the productivity of European forests, showing average European NPP to be about 17% lower than NPP derived with global climate input (Zhao and Running, 2010). We hypothesize here that MODIS EURO will also provide robust and realistic productivity estimates for European croplands. Beyond capturing average multi-year plant productivity, MODIS EURO may even be able to identify productivity gaps spatially and temporally due to suboptimal management, since MODIS EURO has already proved to be useful for predicting annual tree mortality (Neumann et al., 2017).

An enhanced understanding of croplands would benefit ongoing discussions on trading carbon for food (West et al., 2010), and for better managing available land under yield stagnation in many parts of the world (Brisson et al., 2010; Lobell et al., 2011). The C in harvested crops is mainly consumed and respired quickly, so does not represent a significant C sink, except potentially in agricultural soils (Smith et al., 2010). Nevertheless, there should be substantial in situ C storage in crop plants during the vegetation period, so we need robust information on C uptake of agriculture (in addition to forests) to better manage the global land surface to provide resources (food, timber, fiber, etc.) and C sequestration (in situ stocks, substitution of fossil products, etc.).

This study has the following objectives:

- evaluate productivity of agricultural lands temporally from 2000 to 2012 by comparing terrestrial reference NPP using EUROSTAT data, MOD17 NPP and potential NPP calculated using the Miami model and global crop models,
- assess the potential to increase carbon uptake using productivity gap analysis, comparing potential and actual NPP, and
- explore the potential of the methods used here to assess carbon uptake across land use types

2. Materials and methods

Consistent spatially- and temporally-explicit information on C allocation would enable C uptake by vegetation to be quantified independent of country borders, inventory design or missing data. MODIS data allows estimation of plant productivity using the MOD17 algorithm (Zhao et al., 2005; Zhao and Running, 2010), which integrates biogeochemical principles with daily climate input and provides annual NPP and GPP (Net and Gross Primary Production). MOD17 was developed and globally parametrized in the early 2000s using NPP observations (Zhao et al., 2005). We evaluate crop NPP provided by MOD17 temporally from 2000 until 2012 using terrestrial reference NPP and potential NPP calculated using the Miami model (Lieth, 1975) and global crop models (Elliott et al., 2015; Mueller et al., 2012).

2.1. MOD17 NPP

MOD17 provides information on annual C uptake of all terrestrial vegetation types. Such information can be validated with reference data such as forest inventory data for forests (Neumann et al., 2016b) or yield statistics for agricultural land (Monfreda et al., 2008). To our knowledge MOD17 output has not before been validated with European yield statistics. MOD17 employs the radiation use efficiency logic introduced by Monteith (1972) and accounts for C lost by respiration by incorporating basic allometric relations in a respiration module (Zhao and Running, 2010). The key inputs are gridded meteorological data (minimum and maximum temperature, precipitation), remotely sensed vegetation properties (Leaf Area Index, Fraction Absorbed Radiation) and physiological biome properties (e.g. Specific Leaf Area, Maximum light Use Efficiency) pertaining to the local biome type. The MOD17 algorithm is explained in more detail elsewhere (Neumann et al., 2016b; Zhao et al., 2005; Zhao and Running, 2010).

MOD17 provides NPP estimates for a total of 11 land cover types such as evergreen needleleaf forests, mixed forests, grass- and croplands based on the MOD12Q1 land cover map, which uses the University of Maryland (UMD) classification system (Friedl et al., 2010). The MOD12Q1 algorithm for grasslands is parametrized to capture regions with continuous cover with herbaceous plants (Friedl et al., 2010; Hansen et al., 2000). "MODIS grasslands" are thus mostly found in high elevation and in Turkey (Fig. S1) and do not capture pastures or meadows used for grazing, an important type of European agriculture, which appear in the "croplands" category. We evaluated MODIS land cover with two other data sources (EUROSTAT, CORINE land cover) to quantify the share of pasture and test its accuracy. Our study region is constrained by availability of MODIS EURO and EUROSTAT data and covers EU-27, including Norway, Switzerland and the Balkans (Fig. 1).

We used MODIS EURO, obtained by re-running the MOD17 algorithm with downscaled climate data from the E-OBS database