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Estimating agro-ecosystem carbon balance of northern Japan, and comparing the change in carbon stock by soil inventory and net biome productivity

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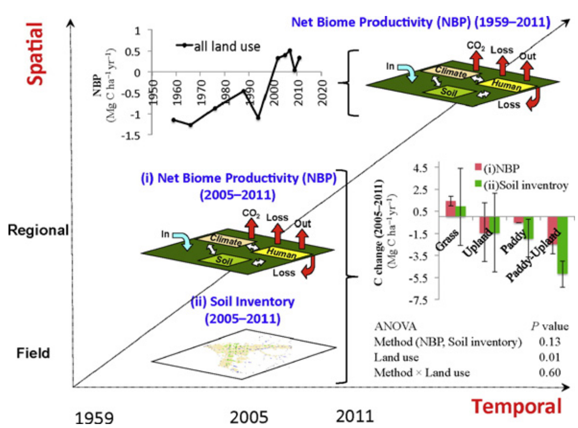
HIGHLIGHTS

- We compared C stocks change by two methods: (i) net biome productivity (NBP) and (ii) soil inventory.
- Variation in net primary productivity (NPP), plant C input, NBP can be predicted by climate conditions.
- NBP decreased in upland and paddy fields under the recent C input scenario.
- In the case of land use change, the regional C pools slowly start to build up.
- There is no significant difference in two methods (NBP & soil inventory).

GRAPHICAL ABSTRACT



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ABSTRACT

Soil C sequestration in croplands is deemed to be one of the most promising greenhouse gas mitigation options for agriculture. We have used crop-level yields, modeled heterotrophic respiration (Rh) and land use data to estimate spatio-temporal changes in regional scale net primary productivity (NPP), plant C inputs, and net biome productivity (NBP) in northern Japan's arable croplands and grasslands for the period of 1959–2011. We compared the changes in C stocks derived from estimated NBP and using repeated inventory datasets for each individual land use type from 2005 to 2011. For the entire study region of 2193 ha, overall annual plant C inputs to the soil constituted 37% of total region NPP. Plant C inputs in upland areas (excluding bush/fallow) could be predicted by climate variables. Overall NBP for all land use types increased from −1.26 Mg C ha^{-1} yr^{-1} in 1959–0.26 Mg C ha^{-1} yr^{-1} in 2011. However, upland and paddy fields showed a decreased in NBP over the period

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of 1959–2011, under the current C input scenario. From 1988, an increase in agricultural abandonment (bush/fallow) and grassland cover caused a slow increase in the regional C pools. The comparison of carbon budgets using the NBP estimation method and the soil inventory method indicated no significant difference between the two methods. Our results showed C loss in upland crops, paddy fields and sites that underwent land use change from paddy field to upland sites. We also show C gain in grassland from 2005 to 2011. An underestimation of NBP or an overestimation of repeated C inventories cannot be excluded, but either method may be suitable for tracking absolute changes in soil C, considering the uncertainty associated with these methods.

1. Introduction

The carbon (C) balance in terrestrial ecosystems has large implications on the variation in atmospheric carbon dioxide (CO_2) emission. Soils have the potential to sequester organic matter and thus to significantly contribute to the terrestrial C sink. Agriculture, being a highly managed system, profoundly affects global C, water and nutrient cycling, as well as the planetary surface energy balance (Bondeau et al., 2007). Both land-use change and agricultural management are important and manageable factors in the C balance of soils and help to mitigate atmospheric CO_2. The greenhouse gas (GHG) emission mitigation potential of agriculture has been estimated as 5.5–6.0 Gt CO_2-eq.$^{-1}$ globally, with 89% of it by means of soil C sequestration using combined measures, such as cropland conversion, cropland management, grassland management or restoration of organic soils (UNFCCC, 2008). It is recognized that agricultural soils can be a significant sink, by adopting appropriate improved management practices and therefore can contribute to mitigating atmospheric CO_2 emissions (Lokupitiya et al., 2012; Smith et al., 2007).

Assessment of soil C stock changes over time is typically done by two methods, namely: (i) repeated soil inventory and (ii) C mass balance approach by continuous measurement of CO_2 exchange in combination with C imports and exports (Leifeld et al., 2011). Repeated soil inventory methods are measure changes in total soil organic C over long periods of time from years to decades (Smith et al., 1997). In many sites, soil organic matter concentration has been measured for several years, but calculations of total soil organic C content has been hindered by the absence of data on soil bulk density and differences in sampling techniques (e.g. no standardization of soil depth and of soil layers) (Smith et al., 2010). Estimates of soil C budgets using soil inventory methods do not account for dead organic matter C, and are limited by spatial variability (Leifeld et al., 2011). The C mass balance approach is the change in carbon stocks after accounting for carbon losses due to natural or anthropogenic disturbances, the mass balance approach could overcomes the limitations of soil inventory studies by integrating the C budget over the whole ecosystem (Leifeld et al., 2011). NECB is the net rate of organic plus inorganic C to or loss from an ecosystem, regardless of the temporal or spatial scale at which it is estimated (Chapin et al., 2006). Extrapolation of NECB to larger spatial scales has been termed “net biome productivity” (NBP) (Schulze and Heimann, 1998; Buchmann and Schulze, 1999).

Many recent studies have used process-based models to quantify NBP of croplands at the continental scale (Wattenbach et al., 2010; Ogle et al., 2010) using soil, climate, land use and management activity data. However, the main difficulty to apply such models at the regional level is data scarcity. In many parts of the world, high spatial resolution of soil data and land-use data are poor or non-existent (Smith et al., 2010). NBP is usually estimated as NECB (NBP) = NPP − Rh − C_{export} + C_{import}. NPP, Rh, C_{export} and C_{import} are the net primary productivity, heterotrophic respiration, C transferred from the system and C input to the system, respectively (Smith et al., 2010). Recently, estimating cropland NPP using crop yield statistics from governmental bodies and crop-specific allometric relationships has become more common for large spatial scales (e. g. Prince et al., 2001; Bolinder et al., 2007; Kimura et al., 2011; Koga et al., 2011). The main advantages of using crop yield statistics in estimating cropland NPP arise from their: (i) spatial explicitness, (ii) flexibility over a range of crops, (iii) reflection of local varieties and field management practices confined to study area and (iv) allowing a simple estimation of annual plant C inputs.

Long-term trends in agricultural productivity and residue inputs to soil, driven by technological and management changes, impact the magnitude and direction of change in soil C storage (Johnson et al., 2006). Due to high NPP of many agricultural crops, relative to non-cropland vegetation, regions converted by agricultural land use can substantially increase short-term C exchanges between the land surface and the atmosphere. Interannual climate variability and changes in crop species distribution, as well as interannual variability in net ecosystem C storage, will have an impact on estimating short-term changes in terrestrial C balances, for both atmospheric-based estimates of regional C cycling and ground-based soil C inventories. A large proportion of NPP (about 40–50% of above ground biomass, which is in the form of grains in crop lands) is removed as yield and thus the long-term C balance in croplands is governed by the amount of crop residues that remains on the field post-harvest. Thus spatio-temporal variability of C inputs has a significant impact on estimating C balance in agricultural ecosystems.

In principal, the value of C mass balance approach for an agricultural system should be directly comparable to the C stock change measured by repeated sampling of soil. However until now, there have been very few field studies that directly compared the two approaches at regional scale (Soussana et al., 2010). Additionally, comparison of estimates derived from soil inventory and the C mass approaches expressed by two distinct concepts (NECB and NBP), lead to miscommunication and potential confusion (Leifeld et al., 2011; Zhang et al., 2014).

The first goal of our study was to explore the trends and inter-annual variability of NBP in upland, paddy fields and grassland ecosystems at regional scale, by focusing on spatial-temporal patterns of NPP and crop residue inputs from 1959 to 2011. Secondly, we compared the change in ecosystem C stocks from 2005 to 2011 by two estimation methods: (i) from repeated soil inventory and (ii) full C budget (NBP) of major dominant land use types in the study area.

2. Material and methods

2.1. The study site

The study site is the Ikushunbetsu River watershed (43°14′N, 141°57′E), which covers an area of 35,887 ha, located in central Hokkaido, Japan (Mu et al., 2008). The 30-year average temperature of this watershed is 7.4 °C, and the annual precipitation is 1154 mm (Japan Meteorological Agency, 2014). There are 4 main soil types in this study area which include Brown lowland, Gley lowland, Grey lowland and Pseudogley (Hokkaido Central Agricultural Experiment Station, 1971). There are 15 sub soil types under the 4 main soil types and 6 soil textures (Table S1 in Supplementary data). The main agricultural land is under paddy fields (*Oryza sativa* L.), onion (*Allium cepa* L.) and winter wheat (wheat) (*Triticum aetivum*) cultivation. Vegetables, such as soybean (*Glycine max* L.) are the minor crop. The dominant soil type is Fluvisols near the river and Cambisols at higher elevations. A more detailed description of agricultural activities, land management and flux measurements, see Mu et al. (2008); Kimura et al. (2007);