Europ. J. Agronomy 61 (2014) 10–23

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Estimation of past and recent carbon input by crops into agricultural soils of southeast Germany

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ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 11 August 2014
Accepted 11 August 2014
Available online 30 August 2014

Keywords:
Soil organic carbon
Climate change
Crop yield
Root-to-shoot ratio
Harvest index
Rhizodeposition

ABSTRACT

In agricultural soils, the formation of soil organic matter largely depends on the carbon (C) input by crop residues and rhizodeposition, which is thus of decisive importance for the management and prediction of soil organic carbon (SOC) stocks in cropland and grassland. However, there is a remarkable lack of reliable, crop-specific C input data. We used a plant C allocation approach to estimate the C input of major crops and grassland into agricultural soils of Bavaria in southeast Germany. Historic and recent plant C allocation coefficients were estimated and C inputs were calculated for a 60-year period (1951–2010) using long-term agricultural statistics. The spatial distribution of C inputs within Bavaria was derived from county-specific statistical data. The results revealed increases of the C input by 107–139% for cereals, 173–188% for root, forage and leguminous crops and 34% for grassland in the last 60 years. This increase was related to linear yield increases until 1995 despite significant changes of plant C allocation. However, from 1995 onwards, crop yields and related C inputs stagnated, which allowed a robust estimation of recent crop-specific C input values. A total C input of 3.8–6.7 t ha^{-1} yr^{-1} was estimated for cereals, 5.2–6.3 t ha^{-1} yr^{-1} for root, forage and leguminous crops and 2.4 t ha^{-1} yr^{-1} for grassland. These amounts were partly higher compared to estimations in the literature. A generally high spatial variability of C inputs was detected within Bavaria with differences of up to 40% between adjacent counties. The results of this study could be used to optimize the C input of crop rotations and thus promote the formation of soil organic matter and C sequestration in agricultural soils on the basis of a soil carbon model. Moreover, recent estimations of C inputs could be used to model the future development of agricultural SOC stocks. A further stagnation of crop yields and the related C input under an ongoing temperature increase bears the risk of a future decrease of SOC stocks in cropland soils of Bavaria.

1. Introduction

In agricultural soils, the plant-derived input of carbon (C) from above- and belowground harvest residues and rhizodeposition and related humification coefficients is of major importance for soil organic matter formation and related soil functions. Thus, precise estimations of the C input are mandatory to monitor the supply of soil organic matter in agricultural soils and model its future development under a changing climate. However, reliable data on the C input of different crops is still hardly available and often limited to rough general estimations for cropland and grassland (e.g., Kuzyakov and Domanski, 2000). This is mainly related to the fact that an estimation of root biomass and rhizodeposition is challenging. Approaches to quantify rhizodeposition, which is comprised of root exudates, mucilage and root cap cells, revealed a wide range of its contribution to net primary productivity (NPP)

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http://dx.doi.org/10.1016/j.eja.2014.08.001
1161-0301/

of 8 to 65% (Kuzyakov and Domanski, 2000; Hütsch et al., 2002; Nguyen, 2003). Despite the lack of precise C input data, many studies aimed to model the development of soil organic carbon (SOC) stocks of agricultural soils. For example, several studies used an inverse application of the soil carbon model RothC to estimate the C input that is consistent with the observed SOC stock under given climatic conditions (Coleman et al., 1997; Yokozawa et al., 2010; Xu et al., 2011; Gottschalk et al., 2012; Meersmans et al., 2013). However, a considerable deviation between measured and modelled C input was observed (Heitkamp et al., 2012). Therefore, the need of independently derived, reliable C input data was emphasized (Osborne et al., 2010; Kimura et al., 2011; Heitkamp et al., 2012).

A promising approach for an efficient estimation of the C input of crops was proposed by Bolinder et al. (2007). This method is based on the allocation of net primary productivity (NPP) to four different plant fractions, which can be derived from literature and statistical agricultural data. The C input of crops can then be calculated on the basis of relative C allocation coefficients, if the absolute C amount of one of these plant fractions is known. This is normally the case for the crop yield, which is available from agricultural statistics in many parts of the world with a high spatial and temporal resolution. The advantage of this approach is that the C input can be derived for specific crops for any location or point in time provided that corresponding data on the plant C allocation and yields are available. Nevertheless, to date no studies were conducted which used this method for an estimation of the recent C input of different crops on a larger area. Moreover, knowledge about the past C input using historical agricultural statistics could contribute to an improved understanding of SOC in agricultural soils. This study aimed to quantify the C input of major crops into agricultural soils of Bavaria in southeast Germany. Besides an estimation of recent C input values and their spatial distribution within Bavaria, also the chronological development since the end of the Second World War was examined.

2. Materials and methods

2.1. Study area

The state of Bavaria is located in southeast Germany and covers an area of 70,550 km^2. Elevation ranges between 107 and 2962 m above sea level. Due to its location in central Europe, Bavaria exhibits a suboceanic climate that is characterized by a transitional situation between a maritime climate in the northwest and subcontinental influences in the east. The land area of Bavaria can be divided into several agricultural regions (Fig. 1) with specific climatic, phenological, geological, pedogenetic and agricultural characteristics according to Würfl et al. (1984) and Wittmann (1991). In the south of Bavaria, the region of the Alps and Pre-Alps is characterized by high mean annual precipitation (MAP) of >1000 mm and relatively low mean annual temperatures (MAT) between 5.4 and 7.5 °C. On shallow, stony soils, intensive grassland use prevails with up to six swaths per year. Between the Pre-Alps and the Danube River, the Tertiary Hills Region encompasses a small structured mixed landscape. A more temperate climate with MAT of 7.0–7.7 °C, MAP of 700 to 1000 mm and deep, loamy soils provide good farming conditions. Within the northern part of the Tertiary Hills Region and further northwest in Bavaria, small, isolated Loess Regions are prominent. Favourable climatic conditions and very fertile soils allow intensive agricultural production. In northeast Bavaria, the East-Bavarian Mid-Range Mountains are characterized by unfavourable climatic and pedological conditions for agricultural use. Here, only small areas are used as grassland. In the central part of northern Bavaria, the region of Jurassic sediments is characterized by MAT of 7.1–7.2 °C, MAP of around 800 mm and fertile soils. To the northwest, the large northern Bavarian Hill Area exhibits a slightly warmer and drier climate, but sandy, acidic soils and low water availability during the summer months inhibit intensive agricultural production. Further to the west, the Franconian Lowlands are characterized by lower precipitation (<700 mm), higher MAT (7.5–9.2 °C) and clay-rich, fertile soils, which restrict agriculture to drought-resistant crops. In the northeastern part of Bavaria, the Franconian Mid-Range Mountains exhibit a cooler climate (5.2–8.0 °C) and acidic soils, which are mainly used as grassland.

2.2. Estimation of plant C allocation

In order to calculate the C input into agricultural soils of Bavaria for each year between 1951 and 2010, the relative proportions of the four plant fractions agricultural product (R_P), aboveground biomass excluding R_P (R_S), belowground biomass excluding R_P (R_R) and extra-root C (R_E) to net primary productivity (NPP) were estimated for different agricultural crops. The fraction R_P represents the harvested product, which can be located aboveground (e.g. cereals, grass) or belowground (e.g. tuber crops). The remaining aboveground biomass after harvest represents the fraction R_S in form of straw, haulm and other crop residues. The plant fraction R_R is related to the root biomass (excluding the harvested component of tuber crops) and R_E constitutes the belowground C released by roots, often referred to as root exudates or rhizodeposition. Due to possible changes of the proportions of R_P, R_S, R_R and R_E in the period between 1951 and 2010 induced by progress in plant breeding, improved crop management and fertilization, allocation coefficients were estimated both for the beginning (1951–1955) and the end (1995–2010) of the considered period. A stagnation of crop yields after the end of the Second World War (Fig. 2) enabled an estimation of representative allocation coefficients, which were derived from numerous agricultural field studies and reports that were conducted in the post-war period until the end of the 1950s (Table 1). The proportions of R_P and R_S were derived from agricultural statistics for Germany from 1951 to 1955 and from Köhnlein and Vetter (1953). The contribution of R_R to NPP was estimated on the basis of several field studies which determined the root biomass of different crop plants gravimetrically by washing of soil monoliths (Gericke, 1945; Bohne, 1950, 1951; Köhnlein and Vetter, 1953; Könekamp, 1953, 1957; Bommer, 1955; Könnecke, 1957; Simon et al., 1957; Simon, 1960). Mean sampling depth for root biomass determination was 40 cm. The contribution of R_E was estimated to be two-thirds of root biomass according to Kuzyakov and Domanski (2000) and Bolinder et al. (2007).

Recent allocation coefficients (for the period 1995–2010) were derived from agricultural statistical data for Germany as well as literature data from 1995 onwards, as agricultural yields of most crops remained on a constant level after this date (Fig. 2). Mean values of published results were calculated for R_P, R_S, R_R and partly R_E with a mean sampling depth of belowground biomass determination of 40 cm (Bolinder et al., 1997, 1999, 2007; Li et al., 1997; Johnson et al., 2006; Gan et al., 2009; Williams et al., 2013). If no data was provided for R_E, the contribution of rhizodeposition was estimated as described above. Between 1955 and 1995, allocation coefficients were linearly interpolated for each year according to the linear trend of crop yields within this period.

2.3. Calculation of the C input

The annual C input was calculated for all major agricultural crops using the approach of Bolinder et al. (2007): winter and spring wheat (*Triticum aestivum*), rye (*Secale cereale*), winter and spring barley (*Hordeum vulgare*), oats (*Avena sativa*), early and late