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Review

Approaches to model the impact of tillage implements on soil physical and nutrient properties in different agro-ecosystem models

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ABSTRACT

Tillage is a primary field operation aiming to modify the soil structure to favour agronomic and soil related processes such as soil seed contact, root proliferation, water infiltration, incorporation of residues, break down of soil organic matter and land forming. The modification of the soil physical and chemical properties especially in the upper soil layers after a tillage operation can be huge. The application of field-scale crop growth models is a widely accepted tool for process understanding but also to support an efficient and sustainable crop production. Agro-ecosystem models are composed of different sub-modules for certain processes related to crop growth and soil-nutrient and water dynamics in response to atmospheric conditions. In this study, the approaches to simulate the impact of tillage on soil physical properties and on vertical distribution of organic matter and nutrients implemented in 16 different agro-ecosystem models (APEX, APSIM, CropSyst, DAISY, DayCent, DNDC, DSSAT, EPIC, HERMES, HYDRUS-1D, LPJmL, MONICA, SALUS, SPACSYS, STICS, and SWAT) are reviewed. Some of the reviewed agro-ecosystem models simulate the tillage effects on soil bulk density, soil settlement, soil texture redistribution, and several soil hydraulic properties. To some extent, the changes in soil porosity, soil aggregates, and the soil organic matter content are considered. Most models simulate the incorporation or/and redistribution of organic matter, residues or/and nutrients in the soil. None of the models consider the changes in biochemical properties such as changes in soil microbial biomass and activity or redistribution of weed seeds after a tillage operation. This study indicates the urgent need to improve the tillage components in crop modelling due to its obvious impact on various soil and nutrient processes and consequently, on crop growth and yield.

1. Introduction

The global population growth has led to intensive farming systems aiming to achieve a high level of food security (Connor and Mínguez, 2012; Foley et al., 2011; Robinson and Sutherland, 2002). However, intensive agriculture is often accompanied by negative environmental impacts like freshwater pollution through nitrate leaching, fade of biodiversity and increase of soil erosion (Uri et al., 1998; Foley et al., 2011; Stoate et al., 2009). The efficient use of the plant available nutrients for agricultural production is of prime importance to diminish the negative impacts on the environment caused by unsustainable cropping systems (Cassman et al., 2003; Foley et al., 2011). Tillage is a primary field operation in cropping systems and has been part of most agricultural systems throughout history (Köller, 2003). Its objectives include seed bed formation, soil aeration, soil evaporation reduction, improving plant water availability, fracturing of soil crusts, weed and pest suppression and the incorporation of residues (Amézketa, 1999; Köller, 2003). Furthermore, tillage operations aim to improve the plant root penetration and soil nutrient redistribution for an efficient nutrient uptake while reducing nutrient leaching (Wang et al., 2015). Tillage is defined as a physical manipulation of the soil (Köller, 2003) involving the disturbance of soil aggregates and soil structure, the compaction of soil, as well as the redistribution of organic matter and microbial activity (Bronick and Lal, 2005). On the short-term, tillage was found to generally reduce soil bulk density in the topsoil or tilled layer (Dam et al., 2005; Tebrügge et al., 1999; Unger, 1992; Wang et al., 2015) and to increase soil porosity, followed by a natural reconsolidation (Pelegrin et al., 1990). The breaking up of soil crusts and dense layers and the increased porosity associated with tillage, were found to increase hydraulic conductivity and infiltration (Lampurlanés and Cantero-Martínez, 2006; Schwen et al., 2011; Unger, 1992). The incorporation of crop residues with tillage generally also reduces soil bulk density due

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to the formation of voids between the aggregates and clods (Allmaras et al., 1996; Guėrif et al., 2001). Below the tilled layer, different studies showed no differences in bulk density between tillage treatments (Wang et al., 2015) or a stronger compaction in the subsoil, countervailing the mean bulk density of the soil profile (Dimassi et al., 2013). In addition, soil compaction due to heavy traffic and plough pan development may occur below the tillage layer impeding root growth and soil water movement (Kay and VandenBygaart, 2002; Sheaffer and Seguin, 2003). Despite this, long-term studies suggest that different tillage systems do not affect the long-term average bulk density and total porosity (Blanco-Canqui et al., 2017; Green et al., 2003). At the end, the effect of tillage on soil hydraulic properties is controversially discussed, as it depends highly on the site-specific pedo-climatic conditions and management (Green et al., 2003).

Regarding aggregate stability, tillage showed a reducing impact (Bottinelli et al., 2017; Roldán et al., 2005; Tebrügge et al., 1999). In comparison to other land uses, croplands under conventional tillage hold a higher proportion of aggregates of > 10 mm than meadows or forests and substantially lower amounts in the favourable aggregate size classes 2–3 mm and 3–5 mm (Ćirić et al., 2012). Massive aggregation has a negative impact on soil structure by increasing bulk density while decreasing water retention capacity (Boix-Fayos et al., 2001). Soil structure characterized by the structure coefficient, Ks was also found to be lower under cultivated croplands than under forests or meadows (Ćirić et al., 2012). The effect of tillage on aggregate size and stability varies in different soils since the process of aggregation is driven by different factors depending on soil type and texture (Bronick and Lal, 2005; Ćirić et al., 2012).

Next to physical soil properties, tillage also affects biochemical properties. Different studies found that tillage has a negative impact on soil microbial biomass, community structure and enzymatic activities (Álvaro-Fuentes et al., 2013; Roldán et al., 2005; Willekens et al., 2014). Álvaro-Fuentes et al. (2013) observed significant differences for tillage and depth in microbial biomass carbon and soil enzyme activities finding a reduction in the surface layer with tillage, but an increase in the 10–25 cm layer and no difference below the 25 cm soil depth.

Depending on the local site conditions and requirements, different tillage types and methods are used (Morris et al., 2010). Historically, conventional tillage is the common soil tillage practice which is characterized by the complete inversion of soil through ploughing. In contrast, conservation tillage (minimum tillage) includes non-inversion tillage practices and no-tillage (El Titi, 2003). In comparison to conventional tillage, conservation tillage and no-tillage were found to increase soil bulk density and penetration resistance across the tillage layer (Chassot et al., 2001; Deubel et al., 2011; Villamil and Nafziger, 2015), to increase soil water content (Alvarez and Steinbach, 2009; Deubel et al., 2011; Villamil and Nafziger, 2015), to reduce erosion (Uri et al., 1998), to improve soil structure (Ćirić et al., 2012; Dal Ferro et al., 2014) and to increase microbial component and cation exchange capacity (Derpsch et al., 2010). However, the impact on soil physical properties due to conservation tillage varies significantly with soil type and texture (Green et al., 2003; Strudley et al., 2008; Morris et al., 2010). Hansen and Djurhuus (1997) observed no significant effect of tillage on nitrate leaching on coarse sand, but the authors observed significant effect on nitrate leaching on sandy loam after tillage. The impact of tillage on saturated hydraulic conductivity and infiltration rate also varies significantly with soil type (Alvarez and Steinbach, 2009; Arvidsson et al., 2013; Gomez et al., 1999; Vogeler et al., 2009).

The tillage impact on nutrient redistribution and availability on plant nutrient uptake is much less covered in the literature compared to the impact on soil physical properties. In general, tillage improves the decomposition of crop residues by facilitating contact between plant tissue and soil aggregate surfaces, the primary biome of soil microorganisms (Bronick and Lal, 2005; Cambardella and Elliott, 1992). In addition, tillage distributes organic matter in the soil and thus improves the availability of nutrients for plant growth through the formation of clay-humus complexes and the increase of charged surfaces for nutrient binding.

In conjunction with this, several researchers observed an increase of soil organic matter (SOM) and carbon (SOC) with conservation tillage practices in the top soil layer (Unger, 1992; Pinheiro et al., 2015; Powlson et al., 2012; Schjønning and Thomsen, 2013; Vogeler et al., 2009). In the lower soil layers no difference or a decrease in SOC with conservation tillage were found, suggesting a balanced budget across the soil profile (Álvaro-Fuentes et al., 2013; Roldán et al., 2005). In special cases, conservation tillage can achieve same effect in a different way, e.g. by reducing the exposition of unmineralised peat (organic soil) to the atmosphere and thereby decreasing total C loss (Gambolati et al., 2005). In the upper 10 cm soil layer, accumulation of considerable amounts of total nitrogen, phosphorus (P) and potassium with conservation tillage was observed (Calegari et al., 2013; Spiegel et al., 2007). However, Calegari et al. (2013) found in the same soil profile higher availability of Phosphorous (P) and Potassium (K) below the 10 cm layer. The presence of higher amount of nutrients in the very top soil (0–5 cm) under conservation tillage is also supported by different long-term experiments (Gómez-Rey et al., 2012; Ji et al., 2015; López-Fando and Pardo, 2012). On the other hand, Roldán et al. (2005) observed no tillage impact on available P. Nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching can be reduced by the application of conservation tillage methods compared to conventional tillage in the cropping system (Del Grosso et al., 2001; Benoit et al., 2015), but N_2O emissions were also found to be increased following conservation tillage depending of soil aeration status (Rochette, 2008). Consequently, the understanding of nutrient availability and crop nutrient uptake for agricultural production requires in-depth knowledge of different and complex interacting processes among soil, plant and environment.

Several mathematical simulation models have been developed to simulate crop development and growth at the field and regional scale on the basis of numerous biophysical and chemical processes. Besides being separated in sub-modules for crop phenology, biomass accumulation and yield formation, most crop models also exhibit different mechanistic sub-modules for soil nutrient and water dynamics and field management, which upgrade crop models into full agro-ecosystem models with abilities to also contribute to soil fertility and groundwater issues. However there are distinctions between crop models and agro-ecosystem models. Crop models and agro-ecosystem models can be interchangeably used to simulate crop growth and development including other environmental processes. Hereafter, all models are ambiguously referred to in this study as agro-ecosystem models or models. The different approaches of some models to representatively describe SOM turn-over in the virtual soil has been reviewed (Manzoni and Porporato, 2009) and tested in Smith et al. (1997). Soil moisture dynamics and SOM turn-over with its subsequent N release from mineralisation are essential simulation steps for a meaningful simulation of crop responses to its environment. Tillage affects both, which makes a reasonable representation of tillage impact on the soil–crop system mandatory for e.g. investigating climate change adaptation and mitigation options for agriculture. In some agro-ecosystem models, tillage sub-modules are implemented and connected to other sub-modules (water balance, nutrient cycle and crop growth), accounting for the impact of changes in the soil physical and nutrient properties. However, these sub-modules are often not well documented and the model user has no good basis to judge on the model's ability to simulate tillage effects, e.g. in supporting the discussion of conservation tillage versus ploughing.

On the basis of the mathematical pool concept that almost all of these models use (Campbell and Paustian, 2015), in theory the accumulation of SOM in the uppermost layer under conservation tillage practices leads to faster SOM decomposition and, consequently, to an increase of carbon (C) losses from the total soil profile as compared to conventional ploughing. Experiments on fields with a legacy of less than 10 years of no-till practice report the opposite (Mangalassery et al.,