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Assessing the Climate Regulation Potential of Agricultural Soils Using a Decision Support Tool Adapted to Stakeholders' Needs and Possibilities

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Soils perform many functions that are vital to societies, among which their capability to regulate global climate has received much attention over the past decades. An assessment of the extent to which soils perform a specific function is not only important to appropriately value their current capacity, but also to make well-informed decisions about how and where to change soil management to align the delivered soil functions with societal demands. To obtain an overview of the capacity of soils to perform different functions, accurate and easy-to-use models are necessary. A problem with most currently-available models is that data requirements often exceed data availability, while generally a high level of expert knowledge is necessary to apply these models. Therefore, we developed a qualitative model to assess how agricultural soils function with respect to climate regulation. The model is driven by inputs about agricultural management practices, soil properties and environmental conditions. To reduce data requirements on stakeholders, the 17 input variables are classified into either (1) three classes: low, medium and high or (2) the presence or absence of a management practice. These inputs are combined using a decision tree with internal integration rules to obtain an estimate of the magnitude of N_2O emissions and carbon sequestration. These two variables are subsequently combined into an estimate of the capacity of a soil to perform the climate regulation function. The model was tested using data from long-term field experiments across Europe. This showed that the model is generally able to adequately assess this soil function across a range of environments under different management practices. In a next step, this model will be combined with models to assess other soil functions (soil biodiversity, primary productivity, nutrient cycling and water regulation and purification). This will allow the assessment of trade-offs between these soil functions for agricultural land across Europe.

Keywords: soil functions, climate regulation, carbon sequestration, N_2O emissions, agroecosystems, qualitative decision modeling

INTRODUCTION

Soils in agroecosystems play an important role regulating the global climate as they have contributed substantially to the increase in atmospheric greenhouse gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O) during the past centuries (Ciais et al., 2013; Le Quéré et al., 2018). The conversion of soil organic carbon (SOC) to CO_2 in agroecosystems mainly occurs as a consequence of the conversion of native vegetation to arable land. This process results in an average loss of topsoil organic carbon (OC) of ca. 32 ± 20 % in temperate regions (Poeplau et al., 2011). N_2O is mainly emitted as a consequence of microbial transformations of fertilizer containing reactive nitrogen (N) that is applied on agricultural land. N_2O emissions occur both directly after application on the field or indirectly, after reactive N has been transferred to other ecosystems, as nitrate (NO_3^-) losses or ammonia (NH_3) emissions (Galloway et al., 2003; Zhou et al., 2017). These emissions are not trivial, as greenhouse gas emissions from agroecosystems have constituted ca. 11.2 % of total emissions (mainly as N_2O and CH_4), while the share resulting from land use changes associated with food production was ca. 10.0 % in 2010 (mainly as CO_2) (Tubiello et al., 2015).

The regulation of the global climate is thus an important ecosystem function that soils perform through carbon storage and a reduction of greenhouse gas emissions, referred to as the climate regulation soil function. This soil function is defined here as the capacity of a soil to reduce the negative impact of increased greenhouse gas emissions on climate, among which its capacity to store carbon (C) and to minimize N_2O emissions. In line with the recognition of the importance of the climate regulating function of soils (Schulte et al., 2014), the *4 per mille Initiative: Soils for Food Security and Climate* has been proposed (https://www.4p1000.org/). This initiative aims to increase the amount of OC in soils around the world, not only to reduce atmospheric CO_2 concentrations, but also to improve food production and mitigate soil degradation. The *4 per mille* initiative has received many criticisms (Minasny et al., 2018), mainly related to the magnitude of achievable gains in SOC over the coming decades and social and economic constraints, despite the many benefits associated with increasing SOC stocks (Paustian et al., 2016; Chabbi et al., 2017; Soussana et al., 2017).

Although uncertainties about the achievable magnitude of future soil C sequestration exist, many long-term experiments (LTEs) have shown that the consistent application of certain management practices does increase the OC content of agricultural soils (Paustian et al., 1997; Ogle et al., 2005; Minasny et al., 2017; Chenu et al., 2018). An increase in SOC stocks is achievable through management practices that increase C inputs to the soil, such as the addition of organic fertilizers (Haynes and Naidu, 1998; Sandén et al., 2018), the incorporation of crop residues in the soil after harvest (Lehtinen et al., 2014) or the cultivation of cover crops (Poeplau and Don, 2015). In contrast, practices that aim to reduce SOC losses, such as no-till, generally lead to a mere redistribution of OC along the soil profile while not significantly increasing total SOC stocks (Luo et al., 2010; Powlson et al., 2014). The application of no-till combined with an increase in C inputs to the soils has, however, been shown to be an effective strategy to increase the SOC content (Luo et al., 2010; Virto et al., 2012). When discussing changes in SOC stocks through changes in management practices, two important considerations have to be taken into account (Minasny et al., 2017; Chenu et al., 2018). First, the efficiency with which SOC stocks are increased is negatively correlated to the initial SOC stock. Second, the rate of the increase in SOC stocks is highest in the first years after the initiation of improved management practices and decreases substantially in the following years or decades. Both effects are a consequence of the maximum amount of OC that can be stored in mineral soils, as a function of the applied management (Six et al., 2002; Stewart et al., 2007; Castellano et al., 2015).

Although increasing the OC content of soils can lead to a net removal of CO_2 from the atmosphere, trade-offs with N_2O emissions should be taken into account, as these can reduce or completely offset the climate mitigation effect of certain management practices (Gao et al., 2018). For example, while the application of farmyard manure (FYM) can significantly increase topsoil OC stocks (Bai et al., 2018; Sandén et al., 2018, 2019b), an accompanying increase in N_2O emissions can offset this benefit (Zhou et al., 2017). Similar observations have been made for crop rotations including cover crops, which can increase topsoil OC stocks significantly (Poeplau and Don, 2015), while N_2O emissions can increase substantially when their biomass is decomposed (Basche et al., 2014). The same pattern has been observed in a modeling study at the European scale by Lugato et al. (2018), who found that the climate mitigation obtained by increasing SOC stocks can be canceled out by increased N_2O emissions due to changing management practices in the long term. Also the practice of crop residue incorporation has been shown to increase losses of reactive N in the form of N_2O and NH_3, despite its positive effect on the SOC content of upland soils (Xia et al., 2018). In contrast, also positive interactions are possible. For example, the potential of cover crops to uptake nitrate (NO_3^-) can substantially decrease indirect N_2O emissions and therefore increase their climate mitigation potential (Tonitto et al., 2006; Basche et al., 2014). These trade-offs thus show that the climate regulation potential of soils in agroecosystems depends on both C sequestration and losses of reactive N species, such as N_2O, NH_3, and NO_3^-.

A thorough evaluation of the climate regulation function of soils in agroecosystems therefore requires a holistic assessment of the effect of different management practices on this soil function (Vogel et al., 2018). In addition, interactions between different management practices, the effect of local environmental conditions and trade-offs between C sequestration and losses of reactive N need to be taken into account. As a consequence, evaluating the climate regulation function of soils is not straightforward, with models generally being used to achieve this goal. Ideally, these models should assess different aspects of this soil function for a given combination of environmental conditions and management practices based on knowledge of the relevant processes. In addition, these models should be simple enough to be applicable by non-expert users, while providing reliable simulations based on the limited amount of data that is generally at hand.

A problem associated with existing models is that data requirements often exceed available data, which limits their application to a regional or national scale. For example, the 1D-ICZ (one-dimensional Integrated Critical Zone) model quantifies four different soil functions (biomass production, C and nutrient sequestration, water filtration and biodiversity) using process-based simulations at the soil profile scale (Giannakis et al., 2017), with a focus on the simulation of temporal changes in soil structure and aggregate dynamics. Although these types of models greatly improve our ability to use process understanding to quantify different soil functions, the simulation of these processes requires a large amount of data, while the range of management practices on which this model has been tested is currently still limited (Kotronakis et al., 2017). Other existing tools that have been developed to quantify different soil functions have been calibrated for North America [Fieldprint calculator (https://calculator.fieldtomarket.org), Comet-Farm (http://cometfarm.nrel.colostate.edu/) and HOLOS (Little et al., 2008)] or the global scale (Coolfarm (https://coolfarmtool.org/), which may limit their applicability to European agroecosystems.

To overcome these problems, we developed a relatively simple, qualitative model to assess the climate regulation potential of agricultural soils that can be coupled to similarly structured models assessing other soil functions. This qualitative model aims to inform different stakeholders, such as farmers or farm advisors, about the directional effects of combinations of different agricultural practices on the climate regulation capacity of mineral, non-peatland, agricultural soils. The aim of this tool is not to provide a detailed quantitative assessment of different fluxes of greenhouse gases from agricultural soils, as other tools are available to achieve this [e.g., DayCent; (Parton et al., 1998) or DNDC; (Li et al., 1992)]. Rather, this tool provides the user with qualitative information regarding the capacity of an agricultural soil to perform the climate regulation function. In addition, the aim of this tool is to increase awareness among model users about the multifunctionality of agricultural soils, and the existence of important trade-offs between the performance of these soil functions as a consequence of the applied management. The model has been developed in the framework of the Horizon 2020 Landmark project, which aims to quantify the current and potential supply of different soil functions from farm scale application to the scale of Europe. These are (i) primary productivity, (ii) water regulation and purification, (iii) soil biodiversity and habitat provision, (iv) nutrient cycling and provision and (v) climate regulation. To achieve this goal, decision support tools for every soil function have been developed. These tools have been brought together to assess the trade-offs between different soil functions for a given set of management practices across Europe (Debeljak et al., 2019). The main aims of this paper are (1) to present the model developed to assess the climate regulation function of agricultural soils and (2) to test this model based on available data from long-term field experiments across Europe.

MATERIALS AND METHODS

Model Description

The model has been developed based on the rationale that it should make a reliable assessment of the climate regulation function of agricultural soils based on data that is readily available. It is built using multi-criteria decision analyses, in particular the DEX (Decision Expert) integrative methodology for qualitative decision modeling (Bohanec and Rajkovič, 1990; Bohanec et al., 2013; Bohanec, 2017). Using this methodology, the main decision problem (assessing the climate regulation soil function) is broken down into smaller, less complex sub-problems in a hierarchical way. The main concept (the climate regulation soil function) is at the top of the hierarchy and is related to lower-level attributes on which it depends. These attributes represent the characteristics of the system, which are environmental variables, soil properties and management practices. The attributes on the lowest level of the hierarchy are the basic attributes. The intermediate attributes are obtained using integration rules, which also determine how the attributes are combined into the final climate regulation function.

The developed model has two distinct parts that separately simulate (i) C sequestration and (ii) N_2O emissions, both direct (from soils) and indirect (originated from NH_3 volatilization/deposition or NO_3^- leaching) (**Figure 1**), as presented in more detail in the following sections. Although the term 'C sequestration' is generally used to describe changes in the SOC stock that result from a net transfer of C from the atmosphere to the soil (Powlson et al., 2011; Chenu et al., 2018), this term is used here in the broad sense of the capacity of a soil to store C. The assessments are made for the upper 0.3 m of agricultural soils. If one aims to evaluate the current climate regulation function of a soil, input data should represent the average environmental conditions and management practices for the past 5 years. This time span was chosen to account for previous management practices, while avoiding problems with providing the average management for a longer period of time, which might be characterized by multiple changes in management practices. If the aim is to evaluate the effect of potential future management practices, input data should represent the current conditions with the desired change in management practices adjusted accordingly, with predictions being made for the medium term (<10 years). It is noted that the model does not account for potential legacy effects from a previous land use. Consequently, the model only provides information about the effect of the applied management practices on the climate regulation soil function. In the model, all attributes are classified into the categorical variables "low," "medium," and "high," or "yes" and "no." Thresholds to classify quantitative variables into these categories were agreed upon by the members of the Landmark project, as shown in **Table 1**. The model result, i.e., how well a soil performs the climate regulation function, is similarly expressed as "low," "medium," or "high." The latter categories are not explicitly coupled to a quantitative value, due to the lack of a quantitative definition of this soil function. The model has been developed to be applicable to agroecosystems throughout Europe, regardless of crop type.

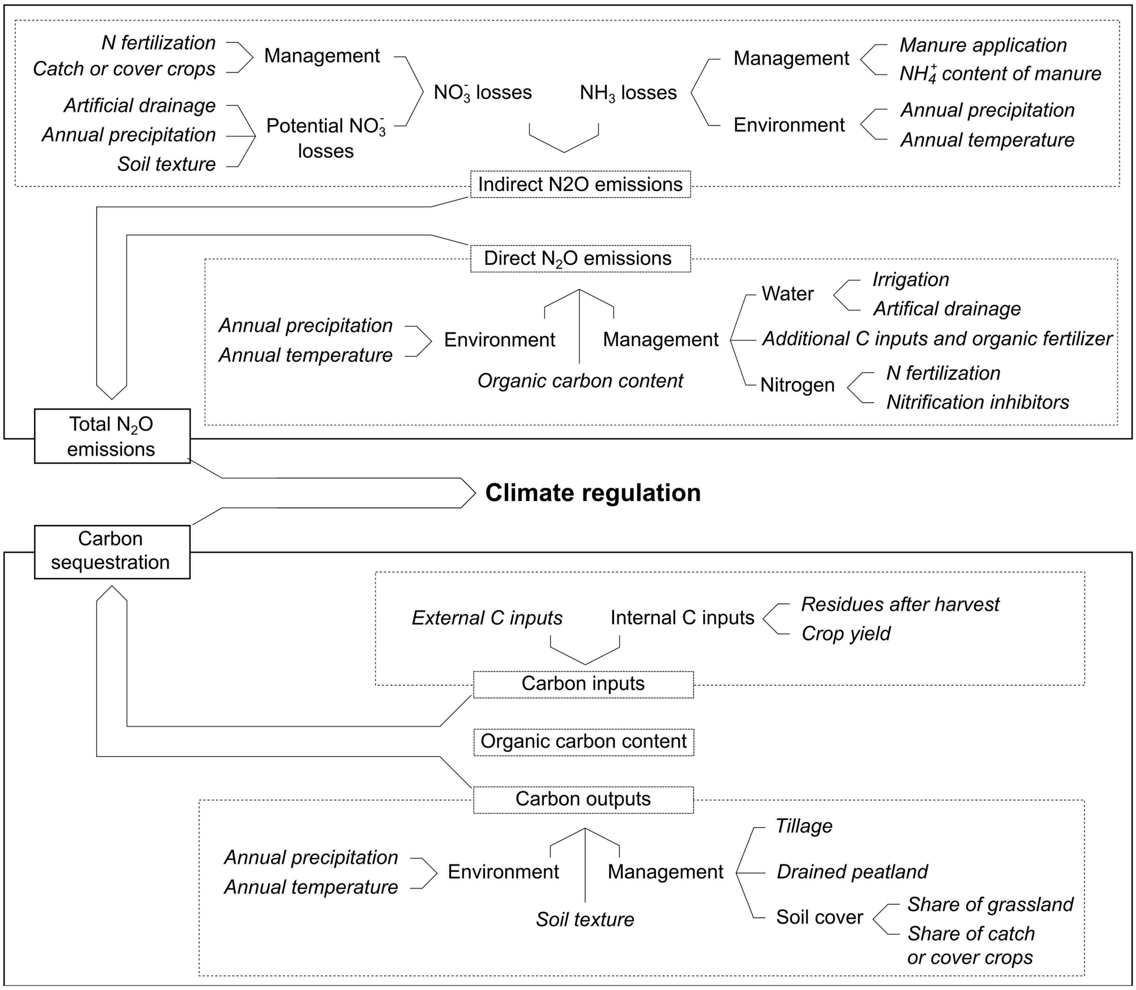

FIGURE 1 | Structure of the model assessing the climate regulation soil function. Input attributes (shown in italic) are classified into "low," "medium," and "high," or "yes" and "no," as shown in **Table 1**. Internal integration rules determine how input attributes are combined into the final climate regulation function, which is similarly classified into "low," "medium," and "high".

More information about how different management practices are translated into model input variables is provided in **Table 1**.

Nitrous Oxide Emissions

The model simulates direct and indirect N_2O emissions separately. Direct emissions are considered as emissions occurring *in-situ* in the field, as a result of the nitrification and denitrification of mineral N derived from applied fertilizer or mineralized organic N. The two sources of reactive N in the model are (i) mineral N fertilizer and (ii) additional C inputs and organic fertilizers (e.g., farmyard manure, slurry and plow-in crop residues). Together with attributes influencing the moisture content of the soil (irrigation and artificial drainage), the magnitude of N inputs determines how management practices influence direct N_2O emissions. The integration rules that determine how the rate of N inputs affects total N_2O emissions are chosen so that the N_2O emissions increase with increasing rates of N application. This is in line with empirical observations, showing that once the amount of applied N exceeds the crop demand, N_2O emissions increase exponentially with every additional unit of applied N (Bouwman et al., 2002; Hoben et al., 2011; Shcherbak et al., 2014). The calculated magnitude of N_2O emissions is further constrained by climatic conditions [N_2O emissions are enhanced by high values of average annual temperature and precipitation, with a higher weight assigned to precipitation (Groffman and Tiedje, 1991; Barnard et al., 2006; Butterbach-Bahl et al., 2013)] and the SOC concentration (high OC concentrations increase N_2O production by providing a substrate for denitrifying bacteria).

Indirect N_2O emissions are the result of the management applied on the field, but occur at downstream locations due to cascading effects (Syakila and Kroeze, 2011; Butterbach-Bahl et al., 2013). The two simulated sources of indirect N_2O emissions occur after leaching of nitrate (NO_3^-) to groundwater, or after NH_3 emissions that are deposited back on the soil surface (Sommer and Hutchings, 2001; Galloway et al., 2003).

TABLE 1 | Thresholds used to categorize input variables into "low," "medium," and "high," or "yes" or "no". Input variable should reflect the average management practices for the past 5 years, while temperature and precipitation inputs should be based on climatic data (30-year average).

	Categories		
Environmental variables			
Temperature (°C)	Low: <6	Medium: 6–10	High: >10
Precipitation (mm yr^{-1})	Low: <400	Medium: 400–900	High: >900
Soil texture	Clayey	Silty	Sandy
Management variables			
Manure application		Yes/No	
NH_4^+ content of manure	Low: Cattle slurry and solid manure; cattle and pig litter; liquid cattle manure		High: Pig and poultry slurry and solid manure; poultry litter
N fertilizer (kg N ha^{-1} yr^{-1})	Low: <50	Medium: 50–100	High: >100
Nitrification inhibitors		Yes/No	
External C inputs for C sequestration	None	Slurry, sewage sludge, digestates	Farmyard manure, compost
Additional C inputs for N_2O emissions	None	Farmyard manure	Slurry, sewage sludge, residues from the main crop, catch crops and cover crops
Organic carbon content (%)	<1	1–3	>3
Tillage	No-till	Non-inversion tillage	Inversion tillage
Residues after harvest left on the field[a] (% of yield)	<10	10–30	>30
Artificial drainage		Yes/No	
Irrigation		Yes/No	
Share of catch or cover crops (years in last 5 years)[b]	<1	1–3	>3
Share of grassland (years present in last 5 years)[b]	<1	1–2	>2
Crop yield (t ha^{-1} yr^{-1})	<4	4–8	>8
Drained peatland		Yes/No	

[a] *Only the aboveground biomass of crop residues should be accounted for.*

[b] *If catch crops, cover crops or grasses are present in the crop rotation, the biomass produced by these crops should be added to the estimation of total crop yield.*

NO_3^- losses are enhanced by the application of N fertilizer and reduced by the presence of catch or cover crops (Hansen and Djurhuus, 1997; Di and Cameron, 2002; Kirchmann et al., 2002). The potential for NO_3^- losses to actually occur is further determined by the presence or absence of artificial drainage, the rate of precipitation and soil texture (Di and Cameron, 2002). The calculation of NH_3 losses is driven by whether or not manure is applied and its NH_4^+ content (Sommer and Hutchings, 2001), while being enhanced by high average annual temperature and precipitation. Attributes that are known to influence N_2O emissions but are not present in the model include the effect of soil pH and different types of (i) compost, (ii) cover crops, (iii) tillage and (iv) irrigation, as discussed in section Discussion.

Carbon Sequestration

The model evaluates the extent to which a soil sequesters C based on (i) C inputs, (ii) C losses, and (iii) the OC concentration of the soil. This soil function is assessed based on the following integration rules: (i) a soil that loses C (outputs > inputs) receives a low value, while (ii) a soil with an increasing C content (inputs > outputs) receives a high value. When (iii) the C stock is in equilibrium (inputs = outputs), the assigned value equals the value of the C concentration. The rationale behind this last rule is that a soil with a high OC content performs the climate regulation soil function better than a soil with a low OC content. It is noted that the model is not designed to make predictions of the OC concentration of the soil. Instead, it evaluates the capacity of a soil to perform the climate regulation soil function while using the SOC concentration as a model input. In addition, the model has not been designed to account for legacy effects on the current SOC concentration, e.g., caused by a recent previous land use. Therefore, the model assumes that the soil has been under cultivation for a timespan of multiple decades. In the model, inputs of C are divided into external and internal inputs (**Table 1**). The former can consist of e.g., farmyard manure or slurry, while the latter consist of the amount of crop residues (as a percentage of the total yield) that is left on the field after harvest and the mean annual crop yield. C outputs are evaluated based on a combination of soil texture, environmental conditions (mean annual precipitation and temperature) and management practices. These include tillage intensity, the share of grasslands and cover crops in the crop rotation and whether or not the soil is a drained peatland. To correctly represent the effect of cover crops or grass in the model, in addition to indicating the number of years a cover crop or grass was present in the past 5 years, an estimate of its biomass has to be added to the mean annual net primary productivity. Attributes that are known to affect C sequestration but are not present in the model include the effect of N fertilizer application, biochar application and soil pH, as discussed in section Discussion.

The Climate Regulation Soil Function

The final climate regulation soil function is determined based on the combination of the magnitude of N_2O emissions and C sequestration. The integration rules that define the magnitude of the climate regulation soil function are shown in **Table 2**. These are a logical combination of the simulated values for N_2O emissions and C sequestration, while a higher weight is given to N_2O emissions because N_2O is a much more potent greenhouse gas than CO_2 and often dominates the GHG balance of agroecosystems. For example, a medium value for C sequestration and a high value for N_2O emissions lead to a low overall climate regulation value.

Sensitivity Analysis

A sensitivity analysis was performed to assess the extent to which the results of the model are influenced by changes in management practices. This was done separately for the simulated magnitude of N_2O emissions and C sequestration, as the combinations of both attributes are straightforward to interpret (**Table 2**). The assessment of how the magnitude of C sequestration is affected by changes in management practices was done relative to a reference management. This reference management was chosen not to favor C sequestration, resulting in low C inputs, high C outputs and therefore low C sequestration (**Figure 3**). The model sensitivity was assessed by gradually changing different management practices which are expected to increase C sequestration. The sensitivity of the N_2O component of the model was assessed using a similar procedure. Here, the reference management was chosen to favor N_2O emissions. Gradually, one, two or three management practices were changed to reduce N_2O emissions. In addition, the effect of average temperature and precipitation on C sequestration and N_2O emissions was assessed for soils with different textures.

TABLE 2 | Integration rules used to classify the climate regulation soil function as "low," "medium," or "high" based on the determined magnitude of N_2O emissions and carbon sequestration.

Carbon sequestration	N_2O emissions	Climate regulation
Low	High	Low
Low	Medium	Low
Low	Low	Medium
Medium	High	Low
Medium	Medium	Medium
Medium	Low	High
High	High	Medium
High	Medium	High
High	Low	High

Model Testing Using Long-Term Field Experiments

An assessment of the accuracy of the model was made by simulating agricultural soils in long-term experiments (LTEs) and comparing the model outcomes to reported changes in N_2O emissions or C sequestration. LTEs were chosen because they facilitate the assessment of a range of different management practices on the component parts of the climate regulation function on a decadal timescale. The geographical location of the LTEs was limited to Europe, in line with the intended geographical extent of model application. For this purpose, the database constructed by Sandén et al. (2018) was used. This database contains publications on 251 European LTEs in which the effect of alternative management practices on soil quality were assessed. From these, 78 LTEs reported on changes in SOC stocks and 40 reported on changes in N_2O emission or NO_3^- leaching. A large portion of these LTEs studied the effect of tillage ($n = 18$ for N_2O, $n = 33$ for C stocks). As the effect of tillage on these soil properties has been summarized in multiple meta-studies, it was chosen not to run all these studies separately by the model, but instead, model performance was assessed based on these meta-analyses (Luo et al., 2010; Powlson et al., 2014; Meurer et al., 2018). After excluding studies on the effect of tillage and studies using parameters that are not simulated by the model, the number of studies that was retained to test the model was 6 for N_2O emissions, 2 for NO_3^- leaching and 12 for changes in SOC stocks. This includes one additional study on NO_3^- leaching (Hansen and Djurhuus, 1997) and one on C sequestration (Spiegel et al., 2018) that were added to the dataset.

The aim of this exercise was to test if the model is able to correctly predict the climate regulation function of (i) a soil with a constant management through time and (ii) a soil which experiences a change in management practices. For the first purpose, the climate regulation function of the control treatments of the LTEs were predicted and compared to reported values. As it was assumed that the OC concentration of the control treatments was constant through time (C inputs equal C outputs), the simulation of the control treatments was used to test if this equilibrium was predicted correctly by the model. Therefore, the classified value of C sequestration by the control treatments was equal to the SOC concentration of these treatments (see section carbon sequestration). For the second purpose, the treatment studied in the LTEs was simulated and compared to the reported change in the soil function. To this end, the results of the LTEs had to be classified into low, medium and high. This was done based on the results reported in the articles presenting the outcomes of the LTEs. The outcomes of the LTEs that were used to validate the C sequestration part of the model were classified based on differences in the SOC concentration between the controls and treatments, as reported in **Table 3**. The outcomes of the LTEs used to validate the N_2O part of the model were classified based on the reported differences in N_2O emissions and NO_3^- leaching between controls and treatments, as reported in **Table S1**. For N_2O, the intensity of emissions for the control situation and the change in management practices was classified (i.e., into low, medium or high) based on the data provided.

The classification of the magnitude of N_2O emissions for the treatment was based on the relative change in N_2O emissions. For example, if the control management (without N fertilizer application) led to low N_2O emissions, a low value was assigned. If the treatment (which included N fertilizer application) resulted in a substantial increase in N_2O emissions, a value higher than low was assigned. Thus, if the model predicted N_2O emissions for the treatment to be medium or high, this was assumed to be a correct model outcome. Also for C sequestration, the classification of the outcomes of the LTEs was based on the data provided in the articles. This information was used to derive the direction of change in SOC concentration as a consequence of the change in management practices, according to the rules outlined in section carbon sequestration. It is noted that term "control treatment" is used to refer to the treatments in the LTEs to which changes in management practices are compared, while the term "reference management" is used to refer to the management practices to which the outcomes of the sensitivity analyses are compared.

RESULTS

Sensitivity Analysis

Carbon Sequestration

The environmental variables (precipitation and temperature) and the soil texture have a substantial effect on the predicted magnitude of C sequestration (**Figure 2**). On average, higher C sequestration is predicted for clayey soils, while this decreases for soils with a coarser texture. Furthermore, the predicted C sequestration is highest for environments with a low temperature and precipitation and decreases when temperature and precipitation increase simultaneously.

The results of the sensitivity analysis of the C sequestration part of the model are shown in **Figure 3**. Increasing the amount of C inputs to the soil (through crop residue incorporation or the addition of external C inputs, not through an increase in yield) from low to medium does not improve the predicted value for C sequestration. When high values for these C inputs are chosen, the predicted value for C sequestration increases from low to medium. When crop residue incorporation and the addition of external C inputs are both at high levels, similar outcomes are obtained. Consequently, for the considered combination of environmental conditions and management practices, only increasing the amount of C inputs while C losses remain high increases the magnitude of C sequestration from low to medium, but not to high. Similarly, the adoption of minimum tillage or no-till does not lead to an increased prediction of C sequestration. As a consequence, only reducing C outputs, while C inputs remain low, does not lead to high predictions of C sequestration. When a management practice that increases C inputs and one that decreases C outputs are jointly applied, medium or high values for C sequestration are predicted. Improving multiple management practices together thus consistently leads to a high predicted value for C sequestration.

N_2O Emissions

The effect of precipitation and soil texture on predicted indirect N_2O losses via NO_3^- and NH_3 losses is shown in **Figure 4**. For the particular combination of management practices chosen (see **Figure 4**), low values of precipitation do always lead to medium predicted values for NO_3^- losses, while medium and high precipitation rates lead to higher losses. On a clayey soil, only high values of precipitation lead to high NO_3^- losses, while coarser soils result in high NO_3^- losses for medium and high precipitation values. This is in line with studies showing that higher NO_3^- losses occur in sandy vs. clayey soils (Gaines and Gaines, 1994; Vinten et al., 1994). Predictions of low NH_3 losses are only obtained at low rates of precipitation, while high losses are consistently predicted for medium and high rates of precipitation. In contrast, temperature and precipitation do not have a marked effect on direct N_2O emissions (data not shown). This is a consequence of the fact that a higher weight is given to the rate of N fertilizer application in the internal decision rules of the model.

The results of the sensitivity analysis of the N_2O emissions part of the model are shown in **Figure 5**. High values for direct and total N_2O emissions are consistently predicted when high rates of N fertilizer are applied. The model predicts decreased N_2O emission when N fertilization is improved (i.e., lower application rates of N fertilizer). Predictions of low total N_2O emissions are not obtained as a consequence of high predicted indirect N_2O emissions in the reference management. Predictions of low direct N_2O emissions are obtained consistently when low rates of N fertilizer are applied.

When management practices that influence indirect N_2O emissions are improved (e.g., no manure application, reduced NH_4^+ content of manure or planting catch crops instead of a fallow period), reduced indirect emissions are only predicted when no manure is applied, or when two or more of these management practices are applied together. However, this does not lead to a decrease in total N_2O emissions in each of these cases, since the reference management leads to high direct N_2O emissions. Optimizing one management practice that reduces direct N_2O emissions and one management practice that reduces indirect emissions only leads to lower predictions of total N_2O emissions when the amount of applied N fertilizer is reduced. Similarly, improving four or six management practices only leads to lower predictions of total N_2O emissions when the amount of N fertilizer applied is reduced.

Model Testing Using Long-Term Field Experiments

For C sequestration, 11 of the 14 control treatments were predicted correctly by the model (**Table 3**, see **Table S1** for additional information), indicating that the model is able to correctly predict the C sequestration function of agricultural soils when no change in OC concentration occurs over time. The model thus correctly simulates that C outputs were equal to C inputs in the control treatments of the LTEs. For treatments that included a change in management practice, 7 out of 14 experiments were predicted correctly by the model. The

TABLE 3 | Model performance using reported data from European long-term field experiments.

References	OC (%)	Texture	T (°C)	P (mm yr^{-1})	Management practice	Expert classification	Model prediction	Correct?
Carbon sequestration								
Blair et al., 2006	1.03	Silt	9.1	693	Control	Low	Low	Y
	2.73				FYM addition	> Low	Low	N
Bolinder et al., 2010	2.3	Silt	3.4	567	Control	Medium	Medium	Y
	2.8				Forage crops and manure	High	High	Y
Jäger et al. (2011) – Spröda	0.71	Sand	8.3	540	Mineral N	Low	Low	Y
	0.83				+ manure	Low	Low	Y
Jäger et al. (2011) – Methau	0.99	Silt	8	600	Mineral N	Low	Low	Y
	1.53				+ manure	> Low	Low	N
Kismányoky and Tóth, 2013	1.07	Silt	10.8	683	Control	Medium	Medium	Y
	1.24				+ manure	High	Medium	N
Triberti et al., 2008	0.54	Silt	13	700	Control	Low	Low	Y
	0.82				+ manure	> Low	Low	N
van Eekeren et al., 2008	1.22	Silt	9.5	726	Control	Low	Low	Y
	1.97				Ley-arable crop rotation	> Low	Medium	Y
Moeskops et al., 2012	1.05	Silt	9.5	726	Control	Low	Medium	N
	1.38				+ FYM	> Low	High	Y
Bertora et al., 2009	1.00	Silt	11.8	740	Control	Medium	Low	N
	1.35				+ FYM	> Medium	Low	N
Monaco et al., 2008	1.04	Sand	11.8	792	Control	Low	Low	Y
	1.41				+ manure/mineral N	> Low	Low	N
Perucci et al., 1997	0.81	Silt	12.6	873	Residue removal	Low	Low	Y
	0.94				Residue incorporation	Low	Low	Y
Šimon et al., 2013	1.17	Sand	7.5	750	Control	Medium	Low	N
	1.49				+ FYM	High	Medium	N
Spiegel et al. (2018) – Marchfeld	1.99	Silt	9.1	540	Control	Low	Low	Y
	2.16				+ crop residues	Medium	Medium	Y
Spiegel et al. (2018) – Alpenvorland	0.84	Silt	8.5	836	Control	Low	Low	Y
	0.87				+ crop residues	Low	Low	Y
Direct N_2O emissions								
Abalos et al., 2013	0.82	Sand	13.2	430	Control	Low	Low	Y
					+ residues	Low	Low	Y
					+ residues & mineral N	High	High	Y
Abdalla et al., 2012	1.6	Sand	9.3	823	Control	Low	Low	Y
					+ N fertilizer	> Low	High	Y
Jeuffroy et al., 2013	1.8	Silt	8	400	Control	Low	Low	Y
					+ N fertilizer	> Low	Medium	Y
Sanz-Cobena et al., 2012	0.8	Sand	13.2	430	Urea addition	High	High	Y
					Urea + nitrification inhibitors	< High	Medium	Y
Sanchez-Martín et al., 2010	0.82	Sand	13.2	430	Control	Low	Low	Y
					+ N fertilizer	> Low	High	Y
Baggs et al., 2006	1.5	Sand	8.4	668	Control	Low	Low	Y
					+ N fertilizer	> Low	High	Y
					+ N fertilizer & residues	> Low	High	Y
Nitrate leaching								
Hansen and Djurhuus (1997) – Jyndevad	1.5	Sand	9	1616	Plowing	High	High	Y
					+ catch crop	< High	High	N
Hansen and Djurhuus (1997) – Ødum	1.5	Silt	7.3	1260	Plowing	High	High	Y
					+ catch crop	Medium	Medium	Y
Constantin et al. (2010) – Thibie	1.5	Silt	10.8	605	No catch crops	High	High	Y
					Catch crops	< High	Low	Y

*T, the mean annual temperature; P, the mean annual precipitation; FYM, farmyard manure; N, fertilizer refers to mineral N fertilizer. The classification of the results for the carbon sequestration part of the model were based on changes in the OC concentration, as reported in the table. More information about the classification of the reported results for N_2O emission and nitrate leaching can be found in **Table S1**.*

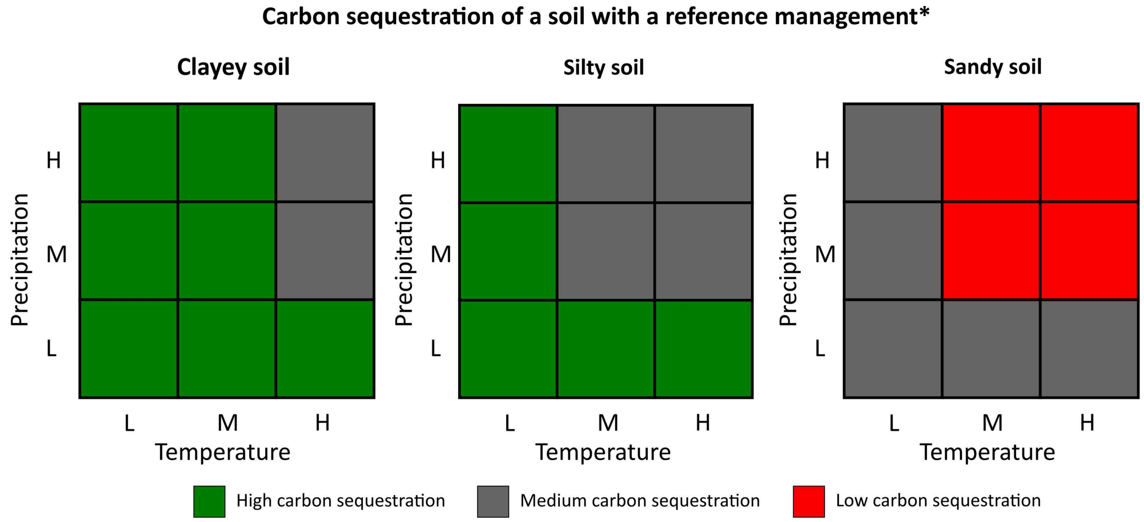

FIGURE 2 | Example of the effect of temperature and precipitation on the predicted C sequestration function of soils with different textures. *Reference management: a mineral soil with medium values for yield, OC content, share of cover crops, external C inputs and residues after harvest; low share of grassland and non-inversion tillage.

management practice that was varied most often was the addition of external C inputs (e.g., manure). The outcomes of the LTEs differed, with some experiments reporting no substantial increase in SOC stocks (Jäger et al., 2011; Kismányoky and Tóth, 2013), while others did report an increase (e.g., Blair et al., 2006; Monaco et al., 2008). In most cases, however, the model did not predict an increase in C sequestration following the addition of manure, in line with the results of the sensitivity analysis. This is a result of the prediction of high C losses for the majority of these experiments, because of the combination of inversion tillage and the absence of cover crops applied in most of these LTEs. As a result, modeled C losses were higher than C inputs in most cases, resulting in low predictions of C sequestration. It should be noted that since most LTEs only report changes in C concentration without reporting changes in bulk density, this may overestimate the amount of sequestered C.

The three LTEs that assessed the effect of crop residue incorporation reported relatively small absolute increases in OC concentrations (0.03–0.17% OC) after multiple decades (Perucci et al., 1997; Spiegel et al., 2018). This was correctly predicted by the model, with no modeled increase in C sequestration for two experiments (with a SOC concentration below 1%) and an increase for one experiment (with ca. 2% SOC). For all these experiments, the incorporation of crop residues led to a high predicted value for C inputs, which was balanced by high predicted OC losses, as a consequence of the application of a combination of inversion tillage and the absence of cover crops in these LTEs. Since modeled C inputs and outputs had an equal magnitude (high), the modeled increase in C sequestration in the experiment with higher SOC (ca. 2 %) in Spiegel et al. (2018) from low to medium was a consequence of the medium OC concentration of this soil.

The only experiment that resulted in high modeled values for C sequestration included both manure application and the presence of forage crops in the rotation (Bolinder et al., 2010), thereby increasing C inputs while reducing C outputs. This was in line with the results from the sensitivity analysis, which showed that the predicted magnitude of C sequestration generally increases when C inputs are increased and C losses are reduced.

The model was successful in predicting the magnitude of direct N_2O emissions for all control (no N fertilizer application) (6/6) and management treatments (8/8) of the LTEs. In most of the LTEs, the control treatment resulted in low N_2O emissions, while most of the treatments included the application of high rates of mineral N fertilizer, leading to higher N_2O emissions. This was predicted well by the model. As shown in the sensitivity analysis, the model predicts high rates of N_2O emissions when high rates of N fertilizer (i.e., > 100 kg N ha^{-1}) are applied, regardless of other mitigation practices. This is in line with studies that have shown that rates of N_2O emission increase exponentially once the amount of N fertilizer exceeds the N requirements of the crops (Bouwman et al., 2002; Hoben et al., 2011; Shcherbak et al., 2014). The addition of crop residues, included as "additional C inputs" in the model, without the application of mineral N fertilizer did not result in higher modeled N_2O emissions, in line with observations (Abalos et al., 2013).

The three LTEs that reported on NO_3^- leaching assessed the effect of the incorporation of catch crops in the crop rotation cycle. The experiments by Hansen and Djurhuus (1997) were performed under similar environmental conditions and management practices, while soil texture differed between the experiments. Although the authors reported a decrease in NO_3^- leaching following the growth of catch crops, the model

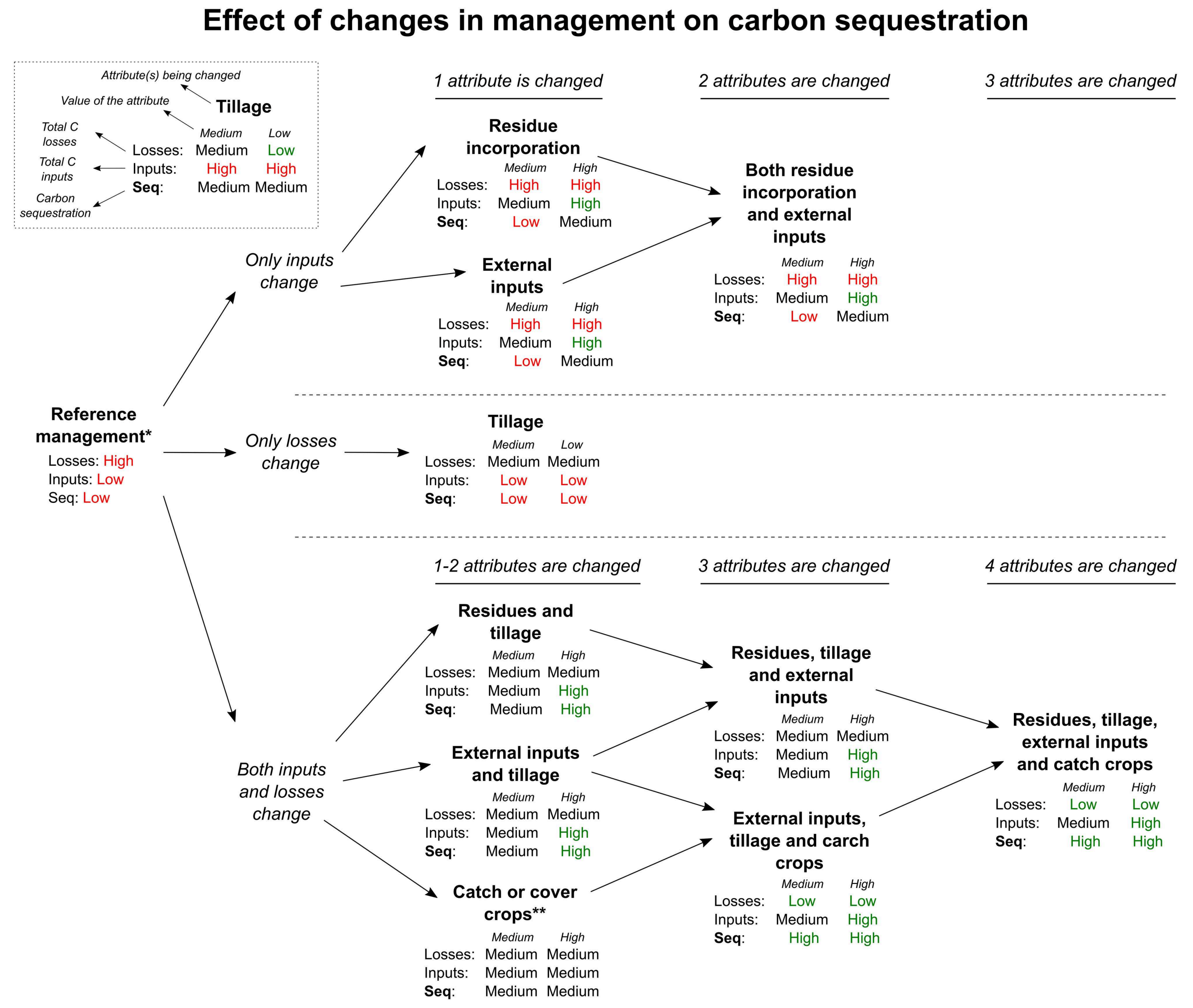

FIGURE 3 | Sensitivity analysis of the C sequestration part of the model (**Figure 1**), based on variations in management practices. The model outcomes are compared to a *reference management: a silty mineral soil with a low yield and medium values for temperature, precipitation and C content, no drainage and management practices that do not favor C sequestration, leading to low C inputs and high C losses. The inset in the upper left corner shows the legend. ** The effect of catch or cover crops is simulated by a reduction of C losses, while an increase in NPP accounts for increased C inputs.

predicted a decrease in NO_3^- leaching only for the silty soil, while no decrease for the sandy soil was predicted because of the high precipitation rate. Also the model predictions for another experiment, which measured the effect of catch crops on NO_3^- leaching in a silty soil, were in line with observations (Constantin et al., 2010).

The effect of different tillage practices on SOC sequestration and N_2O emissions has been studied in numerous long-term field experiments. Although it was initially assumed that the adoption of no-till or minimum tillage increases the SOC content, multiple studies and meta-analyses have shown that these practices generally only lead to a mere redistribution of OC in the topsoil, while not increasing the OC stock at the soil profile scale (Luo et al., 2010; Powlson et al., 2014; Haddaway et al., 2017). This effect is also simulated by the model, as shown in the sensitivity analysis (**Figure 3**). When reduced tillage or no-till is the only management practice that is changed, C outputs are reduced but C sequestration remains low when C inputs are low. When reduced tillage or no-till is combined with increased C inputs, e.g., the incorporation of crop residues, the model does predict a higher C sequestration. This is in line with field observations, which have shown that reduced tillage or no-till only lead to increased SOC stocks when combined with increased C inputs (Luo et al., 2010; Virto et al., 2012; Chowdhury et al., 2015).

Another management practice that has been studied intensively with respect to its effect on SOC stocks is the presence

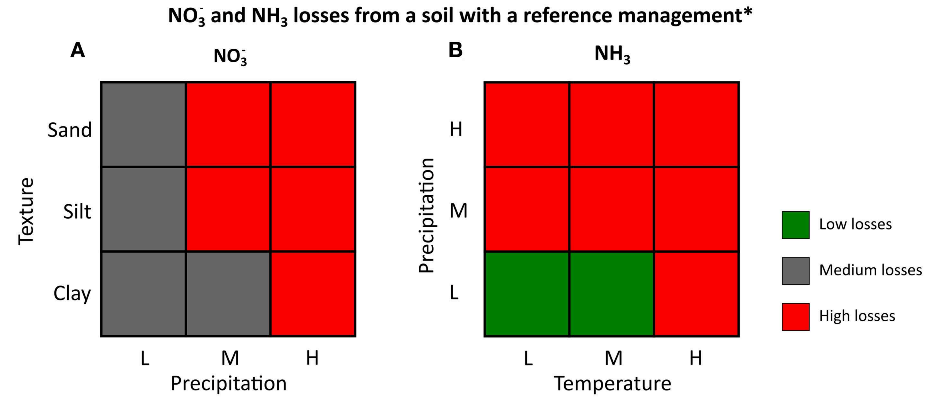

FIGURE 4 | (A) Example of the effect of combinations of texture and precipitation and **(B)** temperature and precipitation on NO_3^- and NH_3 losses respectively. *Reference management for NO_3^- losses: mineral soil without artificial drainage, medium N fertilizer application and no catch or cover crops. Reference management for NH_3 emissions: mineral soil with application of manure with a high NH_4^+ content.

of cover crops between the main crops. Based on data from 37 different sites, Poeplau and Don (2015) calculated that the inclusion of cover crops in the crop rotation cycle leads to a significant increase in topsoil OC stocks on a multi-decadal timescale. In the model, the effect of cover crops is represented in two different ways: (1) through an increase in crop yield, which increases C inputs, and (2) through a reduction in the magnitude of C losses during the time no cash crops are present. When both variables are improved compared to the reference management, similar to the sensitivity analyses (**Figure 3**), the predicted C sequestration increases from low to medium. This modeled increase in C sequestration after the inclusion of cover crops in the crop rotation cycle is thus in line with the results from Poeplau and Don (2015).

Another measure that has been proposed to increase the OC content of agricultural soils is the incorporation of crop residues in the soil (Paustian et al., 2016; Chenu et al., 2018). In an extensive review, Lehtinen et al. (2014) found that the incorporation of crop residues did not lead to a significant increase in the topsoil OC concentration when this practice was applied for $<$10 years, although the effect became apparent after $>$ 10 years. When high rates of crop residue incorporation were considered in the sensitivity analysis (i.e., $>$ 30 % of the yield), the predicted C sequestration increased from low to medium. This model outcome is thus in line with the results from Lehtinen et al. (2014), given that this management practice is maintained over a long period of time.

DISCUSSION

Designing a strategy to manage soils to mitigate climate change is not straightforward, as a thorough understanding of relevant processes at play is necessary. A change in soil management that increases the climate regulation function of soils can cause a decrease in another soil function, such as primary productivity (O'Sullivan et al., 2015; Schulte et al., 2015). Given the complexity of soil systems, models are often used to qualify or quantify the extent to which they perform different functions (Vogel et al., 2018), but the analysis of the multifunctional role of soils in society is still in its infancy. In this study, we presented a qualitative model to assess the climate regulation function of soils. This model has been coupled to similar models simulating other soil functions, in order to assess the trade-offs between these soil functions as a consequence of changes in management practices (Debeljak et al., 2019).

A sensitivity analysis has confirmed that changes in agricultural management practices have an effect on the predicted magnitude of C sequestration and N_2O emissions by the developed model. The predicted magnitude of C sequestration generally only increases from low to high when C inputs are increased while C losses are reduced. If only C inputs are increased, while C outputs remain high, a low predicted magnitude of C sequestration only increases to medium. When only C outputs are decreased, while C inputs remain low, no increase in the magnitude of C sequestration is predicted. This is in line with studies showing that only reducing C outputs, e.g., through the adoption of no-till, only leads to increases in SOC storage when being accompanied by increases in C inputs (e.g., Virto et al., 2012). In addition, the small predicted increase in C sequestration when C inputs are increased, while C outputs remain high, is in line with studies showing that only increasing C inputs can increase SOC concentrations (Lehtinen et al., 2014). Given the fact that the model has been developed for a timescale of several years, while increases in SOC stocks are generally a slow process [in the order of tens of g C m^{-2} yr^{-1} (Paustian et al., 2016; Minasny et al., 2017)], this model outcome is in line with current knowledge, and avoids an overestimation of the C sequestration potential of agricultural soils. With respect to N_2O emissions, the sensitivity analysis showed that the major factor determining the magnitude of predicted N_2O emissions is the rate at which N fertilizer (either mineral or organic) is applied. This is in line with multiple studies that have shown that the magnitude of direct N_2O emissions increases substantially

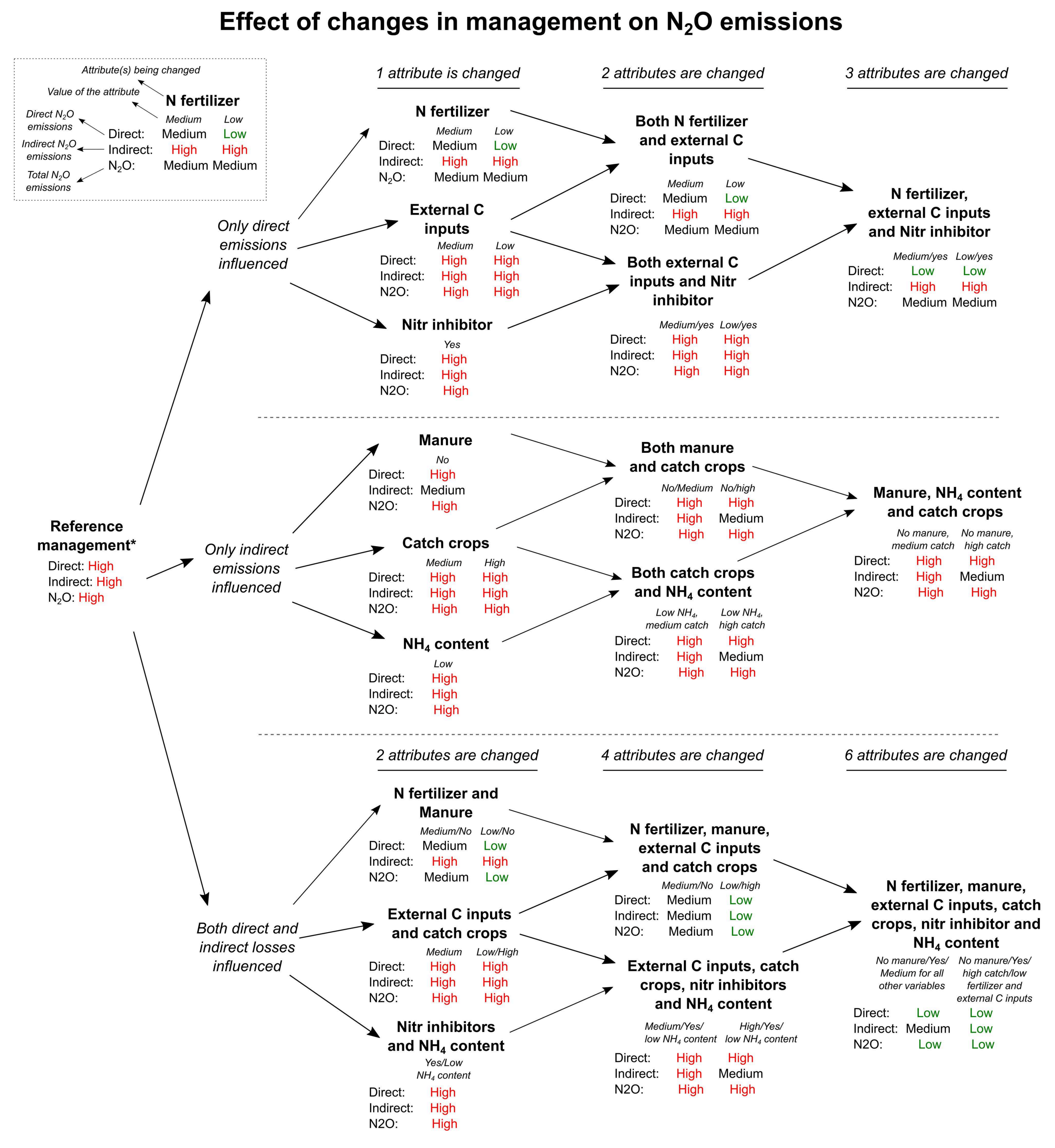

FIGURE 5 | Sensitivity analysis of the N_2O emissions part of the model (Figure 1), based on variations in management practices. The model outcomes are compared to a *reference management: a silty mineral soil with medium values for temperature, precipitation, OC content, no irrigation or artificial drainage and management practices that favor N_2O emissions.

when the plant demand for N is exceeded (Bouwman et al., 2002; Shcherbak et al., 2014).

The verification of the model performance has shown that the model is capable of correctly predicting the C sequestration function of soils that have received a constant management over the past decades (the control treatments). However, the model efficiency was lower for predictions of the alternative management practices that were applied in the LTEs. This was related to the fact that most LTEs assessed the effect of the addition of external C inputs on changes in SOC concentrations. While the model predicts that this has no effect, the majority of the LTEs reported an increase in SOC concentrations. The inability of the model to predict this change can be related to the combination of (i) the classification of inputs data and (ii) the small increase in SOC stocks that is generally observed when improved management practices are applied (10–100 g m^{-2} yr^{-1}; Paustian et al., 2016; Minasny et al., 2017). The effect of other management practices on changes in SOC concentrations (e.g., tillage and cover crops) was predicted adequately by the model. The evaluation of the model performance has thus shown that, in general, the model was able to satisfactorily predict the direction of the change in C sequestration for most of the assessed management practices. However, the effect of the addition of external C inputs on SOC stocks was generally underestimated. Also the effect of the application of N fertilizer on N_2O emissions was adequately assessed by the model in all cases. The magnitude of NO_3^- leaching was correctly predicted in 2 out of 3 cases, indicating that also this management practice is adequately simulated by the model.

The extent to which the model performance could be verified depended on the availability of data from LTEs. With respect to C, the majority of European LTEs evaluated the effect of tillage and the addition of different organic amendments on changes in SOC storage. Other management practices (e.g., the effect of grass in the crop rotation) were assessed in only a few experiments. The main focus of the assessment of the model performance was therefore on the former management practices, while also the effect of cover crops could be assessed based on a meta-analysis (Poeplau and Don, 2015). The performance of the C sequestration part of the model could thus be assessed fairly well. For N_2O emissions, the variation in available LTEs was substantially lower, as they mostly focused on the effect of the rate of N fertilizer application on direct N_2O emissions and the effect of catch crops on NO_3^- leaching. With respect to direct N_2O emissions, management practices that could not be assessed are the addition of external C inputs, irrigation, and artificial drainage. However, while the high rate of N fertilizer application generally has the greatest effect on direct N_2O emissions (Shcherbak et al., 2014), the uncertainties on the effect of the other variables will likely have a limited effect on the overall model uncertainty. The number of experiments used to test the NO_3^- part of the model was limited, but confirmed that the model correctly predicted lower NO_3^- losses as a consequence of the presence of catch crops. Furthermore, the structure of the NO_3^- part of the model is in line with evidence that the rate of NO_3^- losses is enhanced when high rates of N fertilizer are applied (Kirchmann et al., 2002) combined with a downward flux of water at high precipitation rates (Di and Cameron, 2002). In addition, NO_3^- losses were being reduced when catch crops were planted (Hansen and Djurhuus, 1997). In contrast, no experiments that assessed the effect of manure application on NH_3 losses were present. Therefore, this part of the model was constructed based on evidence that high rates of NH_3 emissions are enhanced by high rates of manure addition and a high NH_4^+ content of manure (Sommer and Hutchings, 2001). This part of the model is thus in line with knowledge of the main variables affecting NH_3 losses.

The available dataset allowed to evaluate the model for locations in all three temperature classes, but only for medium and high precipitation classes and silty and sandy soils. As a consequence, the model performance could not be assessed for clayey soils and environments with a mean annual precipitation below 400 mm. Future model evaluations should therefore focus on these environments in order to reduce uncertainties. The crops for which treatment effect were studied in the LTEs included mainly maize, winter wheat, barley and sugar beet, among other less-represented crops (**Table S1**). Some cropping systems, such as orchards, were thus not present in the validation dataset.

The effect of C sequestration and N_2O emissions on the overall climate regulation soil function could not be evaluated, as this soil function is difficult to quantify. In addition, this soil function as such is generally not evaluated in field experiments, but evaluated based on measurements of C sequestration or N_2O emissions separately. The combinations of both C sequestration and N_2O emissions into the climate regulation soil function (**Table 2**) are therefore an attempt to provide the user with an indication of this soil function. As this is an expert-based interpretation, model users are encouraged to look at the modeled magnitude of C sequestration and N_2O emissions to assess how management practices can be changed to improve the overall climate regulation soil function.

Although most of the generally applied management practices are represented in the model, some management practices are currently not included. For example, the effect of different types of compost on N_2O emissions is currently not represented in the model, although it has been shown that this has an important effect on N_2O emissions from agricultural soils (Zhou et al., 2017). However, it was chosen not to include this variable in the model since the effect is highly variable and greatly depends on soil type and climate (Zhou et al., 2017). Another treatment that has been the subject of multiple LTEs is the effect of mineral N fertilizer on C sequestration. Although generally no effect is observed (e.g., Nardi et al., 2004; Triberti et al., 2008; Poeplau et al., 2017), some authors report a small increase in SOC stocks after mineral N fertilization (Dersch and Böhm, 2001; Ladha et al., 2011). However, a potential increase in SOC stocks can be offset by the greenhouse gases produced during the manufacturing of mineral N fertilizer (Gao et al., 2018). Therefore, this has been omitted from the model. However, since the application of mineral N fertilizer generally leads to an increase in crop yields (Jiang et al., 2018), this effect can be included by increasing the NPP model input. Also the effect of cover crops on N_2O emissions was not included as an independent variable in the model. This is because it has been shown that the effect of cover crops on N_2O emissions greatly depends on factors other than the mere presence of cover crops, such as the rate of fertilizer application, the type of cover crop and the potential incorporation of the cover crop in the soil (Basche et al., 2014). Including all these interactions in the model would greatly increase model complexity and, as a consequence, model uncertainty. The addition of an additional C source, such as plowed-in residues of covers crops is, however, included in the model as a variable that stimulates direct N_2O emission. Also the effect of tillage on N_2O emissions was omitted from the model, as it has been shown that there is no significant difference in N_2O emissions under different magnitudes of tillage (no-till, reduced tillage, or inversion tillage) when a timescale more than 10 years is considered (Six et al., 2004; van Kessel et al., 2013). A last set of management practices that is not evaluated by the model to minimize model complexity include the application of different types of irrigation, e.g., drip-irrigation vs. furrow irrigation (Kennedy et al., 2013), biochar application, agroforestry and subsoil management. In addition to considering additional management practices, potential future model improvements may involve adapting the model to simulate (i) managed grassland systems, (ii) managed peatlands, including resulting methane emissions, (iii) the effect of soil pH on C sequestration and N_2O emissions and (iv) methane oxidation.

The model has been developed in the framework of the Horizon 2020 Landmark project, which aims to improve knowledge of the functions performed by European agricultural soils, while developing tools to assess the trade-offs between different soil functions. To achieve this, similar models have been developed for other soil functions: primary productivity (Sandén et al., 2019a), soil biodiversity and habitat provision (van Leeuwen et al., 2019), water regulation (Delgado et al., submitted) and nutrient recycling (Schröder et al., 2016). These separate models are brought together into a tool that assesses the extent to which agricultural soils perform these different soil functions (Debeljak et al., 2019). This allows to assess the win-wins and trade-offs between different soil functions as a consequence of management practices, and represents an important step forward in the quantification of different soil functions in agroecosystems across Europe in order to contribute to the understanding and management of soils to fulfill societal needs.

CONCLUSION

A qualitative decision support tool to assess the climate regulation soil function in European agroecosystems has been developed. This tool has been constructed based on the rationale that it should provide a reliable estimate of the magnitude of C sequestration and N_2O emissions of arable soils using data that is generally available. A sensitivity analysis and an assessment of the model performance based on European LTEs have shown that the model is generally able to correctly assess the effect of different management practices on C sequestration and N_2O emissions. However, the lack of validation data for agroecosystems in dry climates and on clayey soils prevented the model to be validated in these environments. This tool will be combined with similar models to assess trade-offs between different soil functions, in order to inform key stakeholders about the effect of different agricultural management practices on trade-offs between soil functions.

AUTHOR CONTRIBUTIONS

This article resulted from cooperation within the climate regulation task group in the LANDMARK H2020 project. CD, JS, MV, CH, EL, BG, AT, VK, and MD contributed to the development of the model. The validation dataset was constructed by MV, while the validation and interpretation of the results was done by MV, JS, CD, TS, and HS. MV did most of the writing, with major inputs from CD, AT, JS, TS, EL, HS, RC, and BG.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00131/full#supplementary-material

Table S1 | Detailed information about the input data used to validate the model and model outputs.

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