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A system dynamic model to assess exploitability of agricultural residues and effects on soil organic carbon

Tesi di laurea magistrale in Sistemi di gestione ambientale, di politica e di economia ambientale

Relatore:
Dott. Diego Marazza

Correlatore:
Dott. Enrico Balugani

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Federico Orlando

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Abstract

Bio-based products are made from organic materials; the use of crop residuals instead of the actual crops eliminates the competition with the food sector and lowers the costs. However, crop residuals are also an important input of organic carbon in the soil, and are, therefore, important to maintain soil quality and productivity levels.

The aim of this thesis is to evaluate the variation of soil organic carbon (SOC) based on the amount of agricultural residues extracted during harvesting, using a dynamic model. To do so, a System Dynamic model of the turnover of C in soils, based on the RothC model, was implemented. Then, the model was used to simulate the effects of wheat straw removal from the field on the SOC in a Ravenna (Italy) typical soil. A one at a time (OAT) exploratory sensitivity analysis was also conducted to study the model behaviour. The results were stored after 10, 20 and 100 years of simulation.

The results show an inverse linear relationship between the amount of residues extracted and the SOC for all the years analysed. Harvesting the crop residuals can result in a decrease of SOC of ~50%. Other studies found similar results. The sensitivity analysis shows that particular care should be taken in determining the decomposition rate constant of the humus in the soil studied. An observed limitation of the RothC model is that it overestimates the SOC in semi-arid climate; however, this did not affect the results of the present case study.

Literature studies show that the relationship between soil organic carbon reduction and soil quality is not the same for all types of climate and soil, and it is, therefore, difficult to assess the amount of sustainable crop residue extraction. However, using the soil carbon/nitrogen ratio, it should be possible to determine a rough amount of SOC that should be maintained in the soil.

Summary

1 Introduction

Agricultural residues (e.g. wheat straws) can be either left on the field or extracted for other uses; in the first case they would contribute to the organic carbon input to the soil, while in the second case they could be used for construction (e.g. roofs), animal husbandry, or the manufacturing of bio-products. The incorporation of agricultural residues within the soil is an important input of carbon to the soil itself; an adequate carbon balance is necessary to maintain the quality and yield of soils, which, in turns, is required to respond to current challenges posed by a growing world population. We are going towards a continuous growth of the population and consequently a greater demand for food. The 2017’s edition of world population prospect estimates that in 2030 there will be 8.6 billion people living in the world, in 2050 9.8 billion and in 2100 11.2 billion. The FAO estimates that, to meet the population figures for 2050, agricultural production will have to increase by 50% compared to the values of 2012 to meet the greater demand for food (ONU, 2017).

To sustain a higher production of food, high soil productivity is required; however, high soil productivity (in the short term) often leads to an impoverishment of soil quality in the long term and, therefore, to lower yields. Due to the multiple functions that the soil performs, it is difficult to define the concept of soil quality unequivocally (Karlen et al. 1997; Sequi, Benedetti, Dell’Abate, 2006). Soil functions are inherent capabilities of the soil that include biomass and food production, maintaining soil biodiversity, carbon and nutrient sequestration, water filtration and transformation, landscape and heritage, and source of raw materials (Advances in Agronomy, 2017). The Soil Science Society of America (1997) considers soil quality as "the ability of the soil to function within the limits of the ecosystem to support biological productivity, to maintain environmental quality, and promote plant and animal health”. After the same source, the quality of the soil can be defined as the ability of the soil to perform its functions, which, from an environmental point of view, are: food production; agriculture and forestry; the ability to store and partly transform minerals, organic matter, water, energy and various chemical substances; the habitat of a huge quantity and variety of organisms; physical and cultural environment of humanity; source of raw materials.

Determination of the soil quality is very difficult because the relationship between crop yield and soil quality is very complex and depends on complex interactions among physical and chemical properties of soil and other external natural factors. Several articles determine soil quality using different methods or models based on key indicators (De la Rosa and Sobral, 2008; Priyanka and Anshumali, 2016). The key to an appropriate method is the choosing and interpretation of the indicators (Juhos et al., 2016). Soil matrix is an assemblage of mineral particles of various sizes, shapes, and chemical characteristics, together with organic materials in various stages of decomposition and living soil populations (encyclo.co.uk). The stabilisation of organic materials in soils by the soil matrix is a function of the chemical nature of the soil mineral fraction and the presence of multivalent cations, the presence of mineral surfaces capable of adsorbing organic materials, and the architecture of the soil matrix. The degree and amount of protection offered by each mechanism depends on the chemical and physical properties of the mineral matrix and the morphology and chemical structure of the organic matter.

Soil organic carbon, the main topic of this study, plays an important role in determining the quality and fertility of the soil. In Figure 1 the balance of the organic carbon of the soil is illustrated. In general, a budget is defined by the difference between the inputs, the outputs and the storage of the system compartment in question.

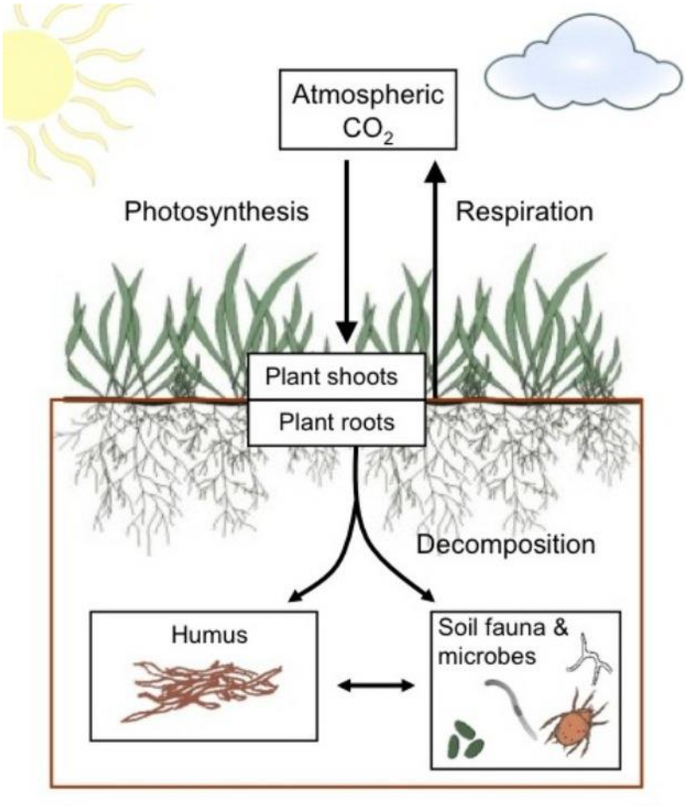

Figure 1 : Carbon balance (Nature Education, 2012).

In agricultural land, there are two types of agricultural crop residues. Field residues are materials left in an agricultural field or orchard after the crop has been harvested. These residues usually include stalks and stubble (stems), leaves, and seed pods; in the case of wheat they are divided into straw and roots. In addition to agricultural residues, manure and fertilizers are two other types of soil organic carbon inputs. For example, manure is used as input in long-term experiments on

Rothamsted fields (Coleman and Jenkinson, 1996) which will be deserved a large attention in this work. The term fertilizer includes substances that, due to their content in nutritive elements or their chemical, physical or biological characteristics, contribute to the improvement of the fertility of the agricultural land, to the nurture of cultivated plants or to the improvement of their development. Fertilizers are subdivided into:

- Fertilizers, which provide crops with the chemical elements of fertility necessary for the plants to carry out their vegetative and productive cycles;
- Amendments and correctives, which modify the chemical, physical, biological and mechanical properties and characteristics of a land, improving its habitability for cultivated plant species.

Agricultural residues, in addition to being buried in the ground to create soil organic matter, can be transformed into bio-based products. The European Committee for Standardization (CEN) defines the bio-based products as: "products wholly or partially derived from biomasses such as plants, trees or animals (CEN)." The extraction of agricultural residues for the realization of bio-based products must be managed in a sustainable manner so as not to have negative effects on the amount of organic carbon in the soil.

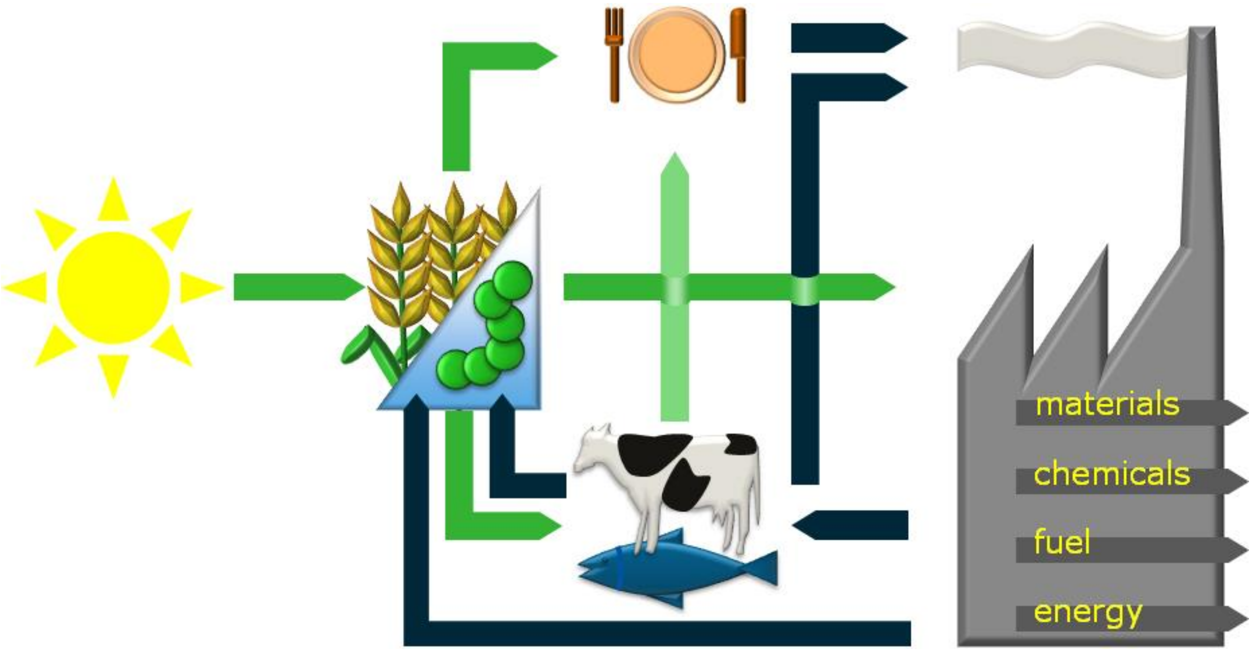

Figure 2: Bio-based economy process (https://www.wur.nl/en/show/Biobased-economy-getting-more-out-of-biomass.htm).

1.1 Goal of thesis work

Since the concept of bioeconomy includes a sustainable use of renewable resources, it is necessary to analyse the amount of agricultural residues which can be extracted from the soil without worsening the quality of the latter. The variation of organic carbon, in relation to the extraction of agricultural residues at the end of the harvesting period, has never been evaluated trough dynamic modelling, as far as the authors know. Therefore, the aim of this thesis is to evaluate the variation of the organic carbon stock of the soil based on the amount of agricultural residues extracted at harvest using a dynamic model.

1.2 Soil organic carbon

The carbon, in particular the organic carbon stock in the soil, is the element which unites what has been said so far to the objectives of the thesis. Carbon in its various forms (inorganic and organic), is cyclically exchanged between the atmosphere, the ocean, the biosphere and geological deposits. The main processes of the carbon cycle are shown in Figure 3. For the purposes of our study, we are particularly interested in the processes that involve carbon in the soil matrix.

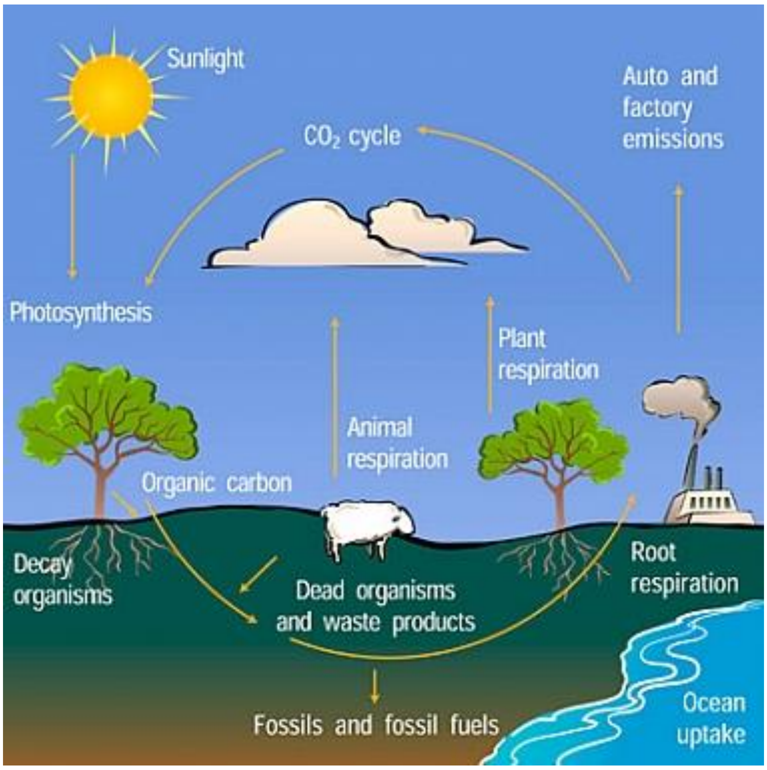

Figure 3 : Carbon cycle (source: eo.ucar.edu).

In principle, the amount of soil organic carbon (SOC) stored in a given soil is dependent on the equilibrium between the amount of carbon (C) entering the soil and the amount of C leaving the soil as carbon-based respiration gases resulting from microbial mineralization and, to a lesser extent, leaching from the soil as dissolved organic carbon. Locally, C can also be lost or gained through soil erosion or deposition, leading to the redistribution of soil C at local, landscape and regional scales. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e. the input of organic C to the soil system) and minimizing the SOC losses (FAO and ITPS, 2015).

Some management practices that can increase SOC and reduce carbon loss into the atmosphere are (Corning et al., 2016):

- Conservation tillage practices, including no-till management aid in storing SOC, keeping the physical stability of the soil intact. When reduced-till systems are combined with residue management and manure management, SOC can increase over time.
- Crop residue management: returning crop residue to the soil adds carbon and helps to maintain soil organic matter.
- Cover crops can increase soil carbon pools by adding both below and above ground biomass. Covers also reduce the risk of soil erosion and the resulting loss of carbon with soil particles. Cover crops also enhance nutrient cycling and increase soil health over time.
- Manure and compost: adding organic amendments such as manure or compost can directly increase soil carbon, and result in increased soil aggregate stability. This enhances the biological buffering capacity of the soil, resulting in greater yields and yield stability over time.
- Crop selection: perennial crops eliminate the need for yearly planting and increase SOC by root and litter decomposition post-harvest. Crops with greater root mass in general add to root decomposition and physically bond aggregates together. Using high residue annual crops can also help reduce net carbon loss from cropping systems (Corning et al., 2016).

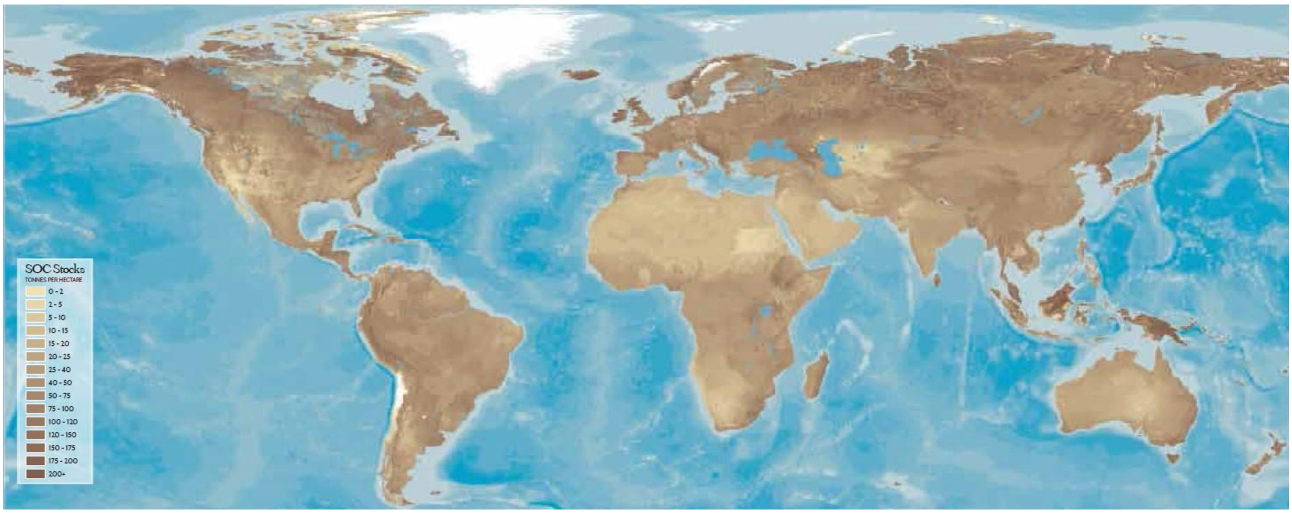

Figure 4: Global soil organic carbon map (source: FAO).

Organic carbon in soils is generated by the degradation of organic vegetable and animal matter by bacteria and fungi. Degradation leads to the formation of two main compounds, the microbial biomass and the humus.

The humus represents the most active portion, under the chemical-physical aspect, of the organic substance of the soil; that portion that interacts with the mineral fraction and with the circulating water solution, influencing the chemical and physical properties of the soil itself and ultimately his level of fertility. The humus acts on the physical properties of the land tending to correct the 'extreme' characters, mitigating for example the excessive fluidity of sandy soils, or the compactness of the clayey ones Foth, (1991). The chemical and structural characteristics of humus have an important effect on soil fertility. In fact, the presence of humus in the ground gives a high adsorbent power to the ground, whose action proves to be relevant to those elements, such as nitrogen and sulphur, more easily subject to leaching, thus maintaining the fertility of the soil. Likewise, elements such as phosphorus and potassium, easily subject to insolubilisation processes if they are adsorbed in the humic molecule, are preserved and made available for radical absorption.

Figure 5 : Humus (www.verdiincontri.com).

CO_2 is emitted back into the atmosphere when the soil organic matter (SOM) is decomposed (or mineralized) by microorganisms. Carbon loss can also be caused by root exudates such as oxalic acid, which liberates organic compounds from protective mineral associations (Keiluweit et al., 2015). Finally, carbon is also partially exported from soils to rivers and oceans as dissolved organic carbon (DOC) or as part of erosion material.

SOC is critical to soil function and productivity, and a main component of, and contributor to, healthy soil condition. Organic carbon in the soil has the dual function of maintaining soil fertility and limiting CO_2 emissions into the atmosphere. Higher soil organic carbon promotes soil structure. This improves soil aeration (oxygen in the soil) and water drainage and retention and reduce the risk of erosion and nutrient leaching. Soil organic carbon is also important to chemical composition and biological productivity, including fertility and nutrient holding capacity of a field. As carbon stores in the soil increase, carbon is "sequestered", and the risk of loss of other nutrients through erosion and leaching is reduced. An increase in soil organic carbon typically results in a more stable carbon cycle and enhanced overall agricultural productivity (Corning et al., 2016).

The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development which were adopted by world leaders in September 2015 identified the need to restore degraded soils and improve soil health (FAO, 2015). Maintaining SOC storage at an equilibrium or increasing SOC content towards the optimal level for the local environment can contribute to achieving the SDGs. This can be achieved by unlocking the full ecosystem services potential of soils to enable not only the support, maintenance or improvement of soil fertility and productivity (necessary to achieve SDG 2 "Zero Hunger" and SDG 3 "Good Health and Well Being"), but also to store and supply more clean water (SDG 3 and SDG 6 "Clean Water and Sanitation"), maintain biodiversity (SDG 15 "Life on Land"), and increase ecosystem resilience in a changing climate (SDG 13 "Climate Action") (FAO, 2015).

1.3 Bioeconomy and land use practices

By bioeconomy we mean the socio-economic system that includes and interconnects those economic activities that use renewable bio-resources of soil and sea, such as agricultural crops, forests, animals and terrestrial and marine micro-organisms to produce food, materials and energy. The bioeconomy, therefore, includes the primary production sector - agriculture, forests, fisheries and aquaculture - and the industrial sectors that use or transform bio-resources, such as the agri-food and pulp and paper sectors, and part of the chemical industry, bio-technologies and energy (Firpo et al., 2016).

Food security, sustainable management and exploitation of agricultural soils, forests, marine flora and fauna and inland waters such as bio-industry are among the factors that most influence society, not only at European level but also worldwide. Bio-economy can be an answer to these problems. The European Commission (EC) defines the bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, biobased products and bioenergy (European Commission, 2012b).

It was in the middle of the 2000s that the bioeconomy entered into policy discussions in the European sphere (European commission, 2012). However, the foundations for the bioeconomy originate from earlier strategic agendas of the European Commission (EC), including the White Paper of 1993 that highlighted the need for non-physical, knowledge-based investments, and the role of biotechnology in innovation and growth (European commission, 1993).

The EC portrays the bio-economy as a key component for smart and green growth (European commission, 2012). The bioeconomy is defined by the EC in its policy package as the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy (European commission, 2012). In addition, the EC background paper for the public consultation determines that a biobased economy integrates the full range of natural and renewable biological land and sea resources, biodiversity and biological materials (plant, animal and microbial), through to the processing and the consumption of these bio-resources. According to the EC (European commission, 2012), the bio-economy in Europe currently has a market size of over 2 trillion Euros and provides 22 million jobs across diverse sectors, including agriculture, forestry, food, chemicals, and bioenergy (cf. BECOTEPS, 2011; Clever Consult, 2010). This contributes to around 9% of the total EU labour force (European commission, 2012). These figures not only highlight the significance of the existing bio-economy to the European economy and society, but also point to opportunities to better integrate activities of different sectors and expand the output of bio-based products. Europe is considered a global leader and pioneer in a number of fields of biosciences and related technologies (European Commission, 2012; ENDS Europe, 2012; McCormick et al., 2013).

The European Union has developed a seven-year program (Horizon 2020) to support and promote research and innovation in Europe. Horizon 2020 is based on 3 pillars: excellent science, industrial leadership and societal challenges. Bio-economy and sustainable agriculture are two of the great challenges of the third pillar European commission, (2014).

The Italian bioeconomy aims to integrate the sustainable production of renewable biological resources and the conversion of these resources and waste into value-added products such as food, feed, bio products and bioenergy. The Bioeconomy Strategy is part of the implementation process of the National Smart Specialization Strategy (National S3) and in particular of its thematic areas "Health, Nutrition and Quality of Life" and "Intelligent and Sustainable Industry, Energy and the Environment", and is implemented in synergy with the "Italian strategy for sustainable development" and its principles to ensure reconciliation of economic growth with environmental sustainability (Firpo et al., 2016).

In Italy the entire Bio-economy sector (which includes Agriculture, Forests, Fisheries, the food and beverage industry, the pulp and paper industry, the tobacco industry, the fibre textile industry, the natural, biopharmaceutical and bio-energy industry) reached a turnover of 250 billion euros in 2015, with about 1.7 million employees. Agriculture is an important sector in Italy, contributing to the value of GDP for around 31 billion euros (2.3%; ISTAT, 2015). The total agricultural area is 17.1 million hectares, of which 12.9 million used. In 2015, the value of production deriving from agriculture, forests and fishing amounted to € 57.7 billion. Approximately 910,000 people are employed in agriculture. Rural development is a very important priority, especially in peripheral areas, characterized by difficulties in accessing services of public interest compared to cities and smaller towns. Agriculture and forestry have great potential in the context of the bio-based and circular economy, in terms of efficient resource management, protection of biodiversity and soil, sustainable land management, production of ecological and social services, exploitation and reuse of residues and waste, as well as in terms of production of bioenergy and biological products, through the adoption of sustainable production models and the efficient use of renewable resources (Firpo et al., 2016).

Therefore, in view of the above, it is necessary to manage land in a sustainable manner, which means by using agricultural techniques that maintain unchanged the amount of SOC. The idea of sustainable agriculture has gained prominence since the publication of the Brundtland Report in 1987, alongside the overarching concept of sustainable development (Tait, J. et al., 2000). Yet, like the notion of sustainable development itself, the concept of sustainable agriculture is ambiguous in its meaning (N. Culleton et al., 1994). Collections of definitions are found in Goldman (1995) and Hansen (1996), and include:

- "For a farm to be sustainable, it must produce adequate amounts of high-quality food, protect its resources and be both environmentally safe and profitable. Instead of depending on purchased materials such as fertilizers, a sustainable farm relies as much as possible on beneficial natural processes and renewable resources drawn from the farm itself." (Reganold et al., 1990).
- Sustainable agriculture is an "integrated system of plant and animal production practices having a site specific application that will, over the long term: (a) satisfy human food and fibre needs; (b) enhance environmental quality; (c) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; (d) sustain the economic viability of farm operations; and (e) enhance the quality of life for farmers and society as a whole." (U.S. Farm Bill, 1990).

Agricultural residues can be buried within the soil or left in the field. These two types of management have different effects on the quality of the soil, and which is better than the two is still the subject of debate.

Regarding the first type of management, the incorporation of residues can improve both the content of soil organic matter (SOM) and the biodiversity of the soil, key elements for the maintenance of the soil structure. The contribution of crop residues to organic matter depends on the type of crop. Cultivation residues with a high carbon content and low nitrogen content are usually more difficult to decompose than those with a low carbon content. The incorporation into the soil can also lead to an increase in nitrate leaching and in nitrous oxide emissions. This is due to a rise in the amount of organic substance containing mineralizable nitrogen Ingram et al., (2014).

Regarding the second type of management, the release of crop residues on the ground guarantees a protective layer of the soil, which otherwise could be naked. The presence of residues reduces the impact of wind and water, the main causes of erosion, also limiting the formation of the superficial crust in finer soils. The presence of residues favours the retention of water in the soil and, improving the structure of the land, determines a better infiltration of the water and its storage in the ground Ingram et al., (2014)

2 Material and methods

2.1 Study area

For this thesis, a hypothetical soil in the Ravenna area is considered. The municipal territory of Ravenna, located at the eastern end of the Emilia-Romagna plain, borders to the north with the municipalities of Comacchio and Argenta, to the west with the municipalities of Alfonsine, Bagnacavallo and Russi, to the south with that of Cervia, Forlì, Bertinoro and Cesena, to the east with the Adriatic Sea. The municipal territory covers an area of 654.88 Km^2.

The territory of Ravenna, completely flat, consists of a coastal alluvial plain generated by the deposits of numerous rivers and streams coming from the Emilia-Romagna Apennines. The lithologies consist of quaternary alluvial deposits, ranging from medium sands, sometimes coarse around the watercourses, to the silty clays laminated in the interfluvial and marsh areas. However, the average clay content of the soils cultivated with wheat is ~ 30% (catalogo dei tipi di suolo del servizio geologico sismico e dei suoli della regione Emilia Romagna). The morphology of the territory is typical of an intensely anthropized floodplain, with hanging riverbeds having raised banks and reinforced by man over the past centuries to both allow the channelled outflow and protect the inhabited and cultivated areas by frequent flooding due to sudden-floods rivers. These cultivated areas found easy and rapid expansion in the land between stream and atrium, sometimes particularly depressed (Piano protezione civile comunale di Ravenna, 2005).

The municipality of Ravenna, from the climatic point of view, can be divided into two units: the coastal strip and the internal plain. The coastal strip is a narrow strip oriented around North-South bounded by the coastline towards the sea, which is clearly influenced by the marine character up to about ten kilometers inland. There is a frequent and sometimes accentuated ventilation, rather low rainfall especially in the northern areas and an accentuated thermal mitigation (Piano protezione civile comunale di Ravenna, 2005). The interior plain, despite being rather close to the previous area, has significantly different characters. It goes from a maritime climate to a more continental one: it increases the daily temperature range with more frequent frosts; the ventilation is more contained, the incidence of fog and of the hot days increases. There is a significant decrease in temperature compared to the coastal area, where the influence of the sea mitigates the climate. The rainfall regime is similar to that of the coastal strip, with a greater frequency of winter snowfall (Piano protezione civile comunale di Ravenna, 2005).

Overall, the climate of the town of Ravenna can be defined as a humid sub-tropical (Cfa according to the classification of Köppen-Geiger), typical of the eastern Po Valley, characterized by maximum precipitation in autumn and sub-maximum in spring, and low rainfall in summer, mostly temporary and minimal in winter (Piano protezione civile comunale di Ravenna, 2005). Table 1 shows the values of precipitation, temperature and evapotranspiration for the city of Ravenna. The temperature and precipitation data were taken from the Dexter portal of the Arpa Emilia Romagna. Monthly data were collected for years 2013-2018 and then the monthly temperature and precipitation average of 5 years was calculated for every month.

The monthly evapotranspiration ET_R was calculated using the Hargreaves equation:

$$ET_R = 0.0135 * R_{S\downarrow} * (T_{mean} + 17.8) \quad (1)$$

$R_{s\downarrow}$ is the incoming short-wave solar radiation in the considered period and was obtained through data taken from the Emilia Romagna Dexter portal. Table 1 shows the trend of the average monthly temperature, of the average monthly precipitation and of evapotranspiration calculated using the Hargreaves equation.

mese	temperatura media mensile [°C]	precipitazione cumulata mensile [mm]	Et0 [mm]	Radiazione solare entrante [J*m^2]
gennaio	5.4	30.5	22.8	72.8
febbraio	7.2	106.2	28.3	83.8
marzo	10.3	70.3	57.2	150.7
aprile	14.8	42	87.7	199.2
maggio	18.3	60.3	141.0	289.4
giugno	23.2	74.1	159.2	287.6
luglio	25.6	24.6	180.9	308.8
agosto	24.9	54.5	168.0	291.4
settembre	20.6	46.9	105.4	203.4
ottobre	15.7	65.3	54.2	119.9
novembre	10.8	95.6	24.3	62.9
dicembre	5.3	40.6	18.6	59.5

Table 1: climatic data for Ravenna (source: portale dexter Emilia-Romagna).

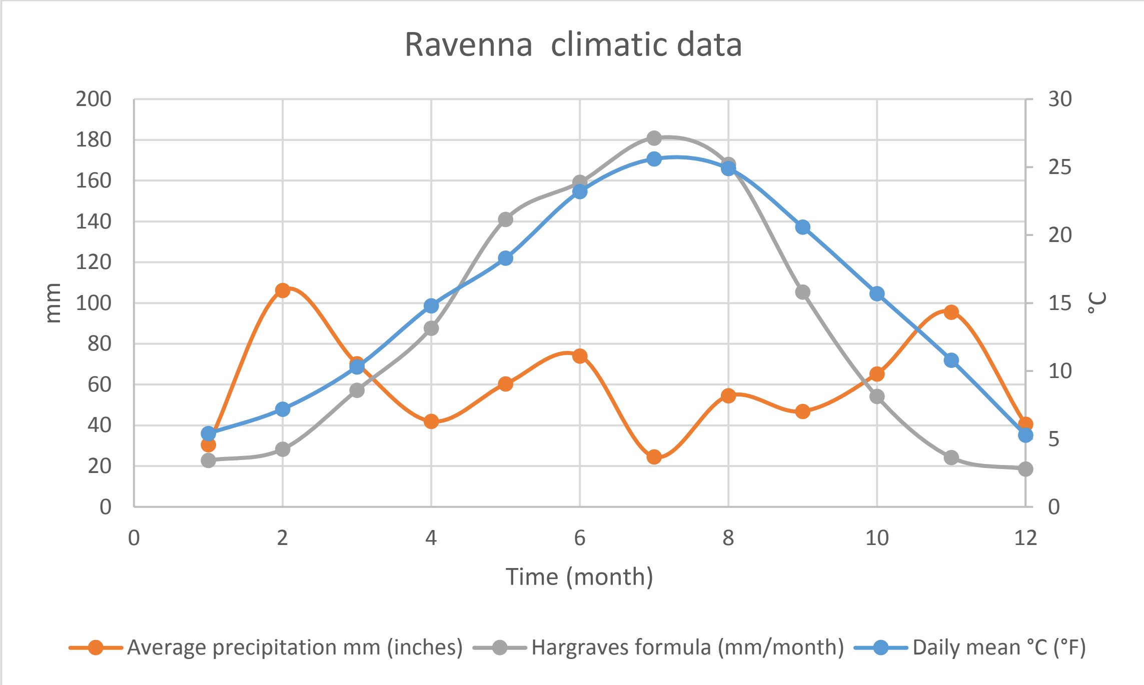

Figure 6: trend of the average monthly precipitation, the average monthly temperature and the evapotranspiration calculated according to the Hargreaves equation.

2.2 RothC model

RothC-26.3 is a model for the turnover of organic carbon in non-waterlogged topsoils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. Between 1843 and 1856, Sir John Lawes and Sir Henry Gilbert established several long-term field experiments at Rothamsted Research (Harpenden). Some failed or were discontinued because of poor soil structure and/or crop diseases. When Lawes died in 1900, the remaining experiments continued more or less as originally planned and are now known as the ‘Classical Experiments’. They are the oldest, continuous agronomic experiments in the world and therefore rightfully and uniquely famous (rothamsted.ac.uk).

RothC-26.3 was originally developed and parameterized to model the turnover of organic C in arable topsoils from the Rothamsted Long Term Field Experiments (Coleman and Jenkinson, 1996), hence the name. Later, it was extended to model the turnover in grassland and in woodland and to operate in different soils and under different climates. The RothC model was calibrated in Australia (Skjemstad et al., 2004), America (Cerri et al., 2003), Europe (Smith et al., 1997; Falloon et al., 2002), New Zealand (Parshotam et al., 1995), Japan (Shirato and Taniyama, 2003; Yokozawa et al., 2010), China (Guo et al., 2007), Kenya (Kamoni et al., 2007), Zambia (Kaonga and Coleman, 2008). Long-term research plays a major role in designing future agricultural systems and understanding the consequences of new practices and technologies. Worldwide, numerous long-term experiments (LTEs) or other long-term research platforms have been established, following a tradition that started with the first classical long-term trials planted in 1843 at Rothamsted in the UK.

RothC-26.3 is designed to run in two modes: ‘forward’ in which known inputs are used to calculate changes in soil organic matter and ‘inverse’, when inputs are calculated from known changes in soil organic matter. The structure of RothC model is shown in Figure 7.

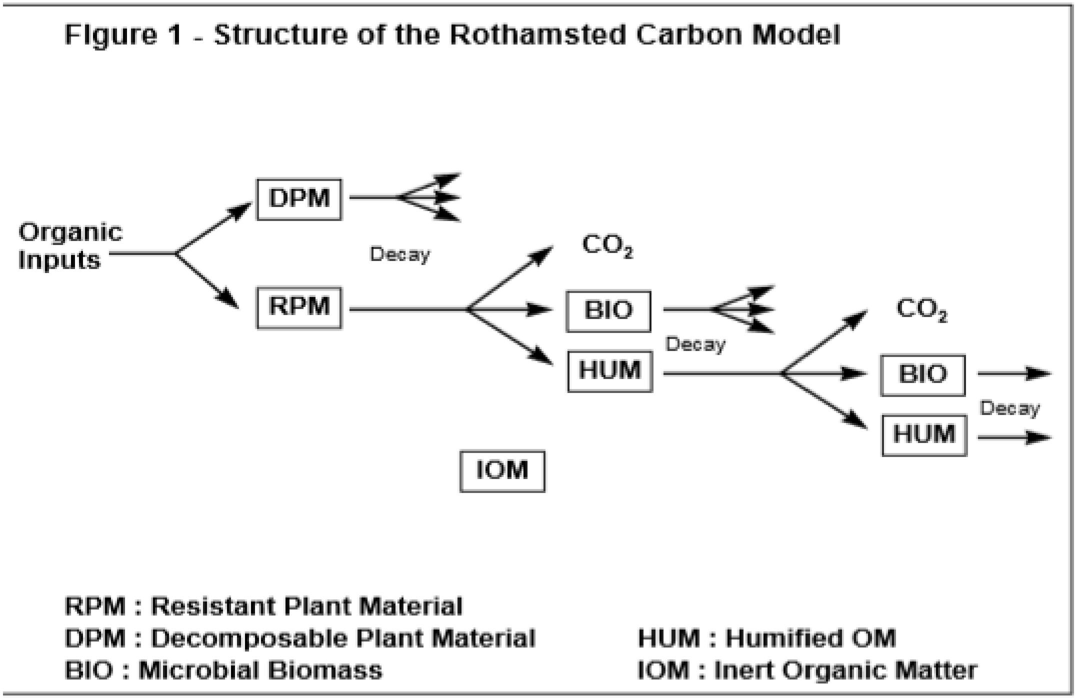

Figure 7: Structure of the Rothamsted carbon model.

In the model, carbon enters the soil as “organic inputs”, which are intended as the set of organic compounds entering the soil, both of animal and vegetable origin. In our case study, the organic input consists in plant residues for wheat cultivation, i.e. straws and roots. The incoming plant carbon is split in two compartments: decomposable plant material (DPM) and resistant plant material (RPM). Both, in contact with the soil and with the passage of time, undergo a process of decomposition. Decomposition is a sequential process whereby complex organic compounds are continuously degraded into simpler substances, releasing nutrients as a byproduct of their breakdown (Yadav, 2007). The decomposition can be divided into different phases: (a) leaching, a term which indicates the loss of organic or insoluble substances by run-off (which in turn is a process of erosive action carried forward by meteoric waters on the surface layers of rocks or soil); (b) fragmentation, reduction and degradation of the litter by detrivorous microorganisms; and (c) catabolism, the chemical alteration of the components of the litter, which includes processes such as mineralization and humification (biosproject, 2011).

The DPM / RPM ratio defines the percentage of agricultural residues that will decompose as DPM and RPM. DPM represents the easily decomposed material, e.g. the cellulosic and hemicellulosic part of the plant, while the RPM represents the part of the plant more resistant to decomposition, e.g. the ligninic part. The value of the DPM / RPM ratio is given by the quantity of cellulose and lignin present in the specific culture.

The difference between DPM and RPM is given, in the model, by the rate of decomposition. The DPM has a higher decomposition rate, compared to the RPM, i.e. in contact with the soil the DPM will decompose in less time than the RPM.

The rate of decomposition is not only influenced by the intrinsic resistance of the molecules according to the type of chemical structure, but also by their interaction with the mineral fraction. Lignin is typically considered to be highly resistant to degradation (Kögel-Knabner 2002), and only specialized biota (predominantly fungi) are able to synthesize the extracellular enzymes that are necessary to break down these recalcitrant structures into biologically accessible forms (Swift et al. 1979). Compared with lignin, cellulose degrades more rapidly during the process of litter decomposition; the decomposition factors can be fungi, with both aerobic and anaerobic bacteria. Moreover, the rate of decomposition is influenced by the climatic conditions, the properties of the structure of the soil and land use.

In the RothC model, each active compartment, when decomposing, transfers carbon to the BIO, HUM and CO_2 compartments, with the ratio of carbon transfer between CO_2 and BIO+HUM defined by the clay content (Subsection 2.2.5). The BIO+HUM carbon is, then, divided in the carbon going to the BIO (0.46 of BIO+HUM) and to the HUM (0.54 of BIO+HUM) compartments. Decomposition rate is controlled by soil temperature and, together with the availability of water, regulates oxidation reactions, plant growth and microbial activity. The texture of the soil plays an important role in the decomposition of organic matter. In soils with high clay content, organic-mineral complexes are formed that protect the organic substance from decomposition, while in sandy soils the decomposition is favoured.

In this model, we have four active compartments. An active compartment decomposes over time to form other compounds. The four active compartments are shown in Figure 6, they are DPM, RPM, Microbial Biomass (BIO) and Humified Organic Matter (HUM). The inert organic matter (IOM) compartment is resistant to decomposition. Each active compartment, (DPM, RPM, BIO, HUM), contains a mass of organic carbon, defined as Y [tc/ha] and over time these compartments decompose to form other BIO, HUM and CO_2. The CO_2, at the end of each time-step, exits the system, acting in this way as a sink of carbon in the model.

The RothC model does not differentiate between soil incorporation and soil release techniques.

To model the impact of residues extraction (straws) from wheat fields in the Ravenna study area, we have studied and extrapolated the equations of the RothC model and transferred them to a more manageable model implemented in System Dynamics (subsection 2.3).

2.2.1 Model input

We need three types of input in order to run the model:

1. Climatic inputs: monthly rainfall (Pm), monthly open pan evaporation (Em) and average monthly mean air temperature (°C) (Ta,m).
2. Soil inputs: clay% and soil sample depth
3. Crop and land usual practices: DPM/RPM; IOM°; monthly bare soil/vegetated soil; monthly input plant residues (OCm) and FYM (farmyard manure).

FYM is assumed to be more decomposed than normal crop plant material. It is split in the following way: DPM 49%, RPM 49% and HUM 2%.

2.2.2 Initial conditions of the experiment

In order to run, the model needs the definition of some initial condition, which are listed below:

- Pm0; Em0; Ta,m; respectively monthly precipitations, evaporation and average temperature;
- DPM°; RPM°; BIO°; HUM°; IOM° (as defined above);
- Clay; depth of soil and IOM are three constants.

2.2.3 Mass balance

At each time step the mass balance is calculated for each active compartment c as follows: $stock_{i,c} = stock_{i-1,c} + input_{i,c} - output_{i,c}$ (2)

Where i is the time step. Equation 1 is used to calculate the carbon content in each active compartment at each time step. The dynamic balance indicates how quickly the material moves between the compartments.

2.2.4 Input of an active compartment

The following are the inputs for each active compartment.

2.2.4.1 Decomposable plant material (DPM)

Looking at Figure 7, we can say that the only input for DPM is the organic material that, in the specific case of our study, it is the wheat straw and roots material. Another input for DPM is the FYM [tC/ha].

Equation 3 represents the input for the DPM compartment.

$$Input_{DPM} = \ Plant\ residues/\frac{1}{(DPM/RPM)+1} + 0.49 * FYM \quad (3)$$

2.2.4.2 Resistant plant material (RPM)

For the resistant plant material, we have two types of input: the vegetable residuals and the FYM. Equation 4 represent the input for the RPM compartment

$$Input_{RPM} = \frac{Plant\ residues}{(DPM/RPM)+1} + \ 0.49 * FYM \quad (4)$$

2.2.4.3 Microbial biomass (BIO)

Since every active compartment decomposes into BIO, HUM and CO_2, the BIO inputs at each time step will come from all the four active compartments.

$$Input_{BIOi} = BIO_{DPMi} + BIO_{RPMi} + BIO_{HUMi} + BIO_{BIOi} \quad (5)$$

The equations obtained for each BIO input are shown below.

$$BIO_{DPMi} = 0.46 * (BIO + HUM)_{DPMi} \quad (6)$$

Where $(BIO + HUM)_{DPM}$ is calculated as follows:

$$(BIO + HUM)_{DPMi} = \frac{DPM_{i-1} * \left(1 - e^{-abck(DPM)^t}\right)}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (7)$$

$$BIO_{RPMi} = 0.46 * \frac{RPM_{i-1} * \left(1 - e^{-abck(DPM)^t}\right)}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (8)$$

$$BIO_{BIOi} = 0.46 * \frac{BIO_{i-1} * \left(1 - e^{-abck(DPM)^t}\right)}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (9)$$

$$BIO_{HUMi} = 0.46 * \frac{HUM_{i-1} * \left(1 - e^{-abck_{(DPM)}t}\right)}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (10)$$

Equations 8, 9, 10 were obtained using the decomposition (output) calculation for the other active compartments (Subsection 2.2.6) and the $\frac{CO_2}{BIO+HUM}$ ratio (Subsection 2.2.5). The factor 0.46 is a coefficient given in RothC for the subdivision of carbon between BIO (0.46) and HUM (0.54).

2.2.4.4 Humified organic matter (HUM)

For this compartment, we have the same situation described for the BIO compartment, meaning that it receives input from all other active compartments. Compared to the BIO compartment, we have an extra input given by the decomposition of the FYM (11). In the model, 2% of farmyard manure decomposes directly in the form of HUM (Subsection 2.2.1).

$$Input_{HUMi} = 0.02 * FYM_i + HUM_{DPMi} + HUM_{RPMi} + HUM_{BIOi} + HUM_{HUMi} \quad (11)$$

The equations for each input of the HUM compartment are shown below:

$$HUM_{DPMi} = 0.54 * \frac{DPM_{i-1} * \left(1 - e^{-abck_{(DPM)}t}\right)}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (12)$$

$$HUM_{RPMi} = 0.54 * \frac{RPM_{i-1} * e^{-abck_{(RPM)}t}}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (13)$$

$$HUM_{BIOi} = 0.54 * \frac{BIO_{(i-1)} * e^{-abck_{(BIO)}t}}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (14)$$

$$HUM_{HUMi} = 0.54 * \frac{HUM_{(i-1)} * e^{-abck_{(HUM)}t}}{\left(\frac{CO_2}{BIO+HUM} + 1\right)} \quad (15)$$

The factor 0.54 is a coefficient given in RothC for the subdivision of carbon between BIO (0.46) and HUM (0.54).

2.2.5 Partitioning of carbon between the CO_2 losses and carbon incorporated in the BIO and HUM soil compartments: the CO_2/(BIO+HUM) ratio

The model adjusts for soil texture by altering the partitioning between CO_2 evolved and (BIO+HUM) formed during decomposition, rather than by using a rate modifying factor, such as that used for temperature.

The ratio CO_2 / (BIO+HUM) is calculated from the clay content of the soil using:

$$x = 1.67 * (1.85 + 1.60e^{(-0.0786\%clay)}) \quad (16)$$

where x is the ratio CO_2/(BIO+HUM). Therefore, x/ (x+1) is evolved as CO_2 and 1/ (x+1) is formed as BIO+HUM.

2.2.6 Output (decomposition) of an active compartment

Each compartment (DPM, RPM, BIO, HUM) contains a mass of organic carbon, defined as Y tC/ha; the output (decomposition) of organic carbon from that compartment is calculated, for each month, as $Y(1 - e^{-abckt})$, where:

- a, is the rate modifying factor for the temperature;
- b, is the rate modifying factor for the moisture;
- c, is the soil cover rate modifying factor;
- k, is the decomposition rate constant for that compartment;
- t is 1/12, since k is based on a yearly decomposition rate.

2.2.6.1 a

the rate modifying factor (a) for temperature is given by:

$$a = \frac{47.91}{1+e^{\left(\frac{106.06}{T+18,27}\right)}} \quad (17)$$

where T is the average monthly air temperature (°C).

2.2.6.2 b

To calculate the top soil moisture deficit (TSMD), some steps are needed.

First, rain and open pan evaporation data needs to be acquired. Then evaporation is multiplied by 0.75 to obtain the “actual evapotranspiration” used by the model. Then, we calculate, for each month, the difference between the value of precipitation and that of evapotranspiration. Finally, we calculate the cumulative TSMD ($TSMD_{acc}$) for each month, constraining it between the conditions of full soil saturation ($TSMD_{acc}$= 0) and maximum dryness ($TSMD_{acc}$= $Max\ TSMD$). Therefore, $TSMD_{acc}$ cannot go below a certain value calculated as in Equation 18.

The maximum TSMD for the 0-23 cm layer of a particular soil is first calculated as:

$$Max\ TSMD = -(20 + 1.3(\%clay) - 0.01(\%clay)^2) \quad (18)$$

For a soil layer of different thickness, the maximum TSMD thus calculated is divided by 23 and multiplied by the actual thickness, in cm.

This means that the accumulated top soil moisture deficit ($TSMD_{acc}$) will begin to accumulate from the first i-th month in which the difference between precipitation and evapotranspiration is negative; that is, from the i-th month in which the evapotranspiration value is greater than the precipitation value. Then, as soon as the precipitation value becomes greater than the evapotranspiration, the soil will start to moist again, reducing the TSMD value. Finally, the rate modifying factor (b) used each month is calculated from:

- If $TSMD_{acc}$< 0.444 * Max TSMD, then b= 1.0 (19);
- Otherwise $b = 0.2 + (1.0 - 0.2) * \frac{(Max\ TSMD - TSMD_{acc}acc.TSMD)}{(Max\ TSMD - 0.444\ Max\ TSMD)}$ (20)

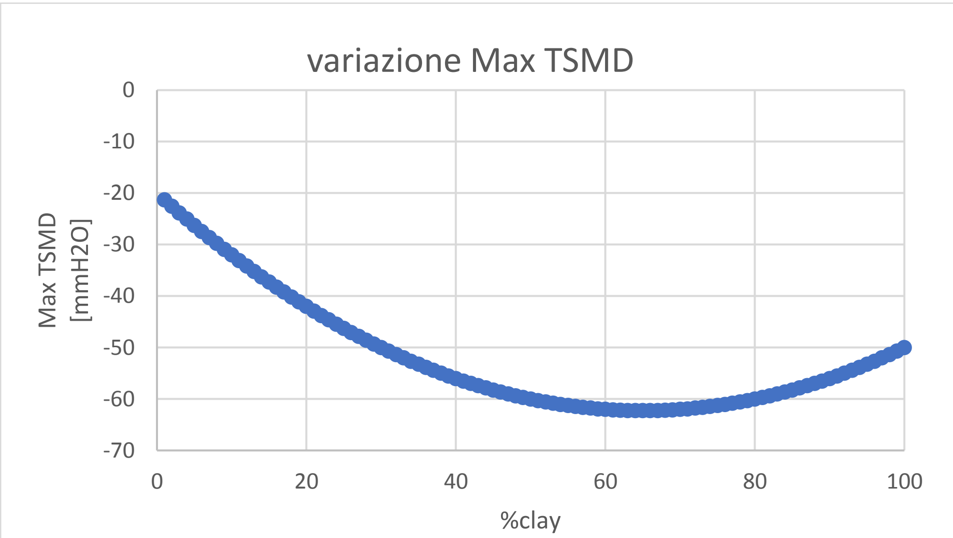

Figure 8: variation of max TSMD (top soil moisture deficit) with respect to clay %. The relationship used in the model was obtained from an experiment conducted in the fields of Rothamsted. A non-linear relation is noted, with a maximum value of -20 corresponding to the minimum percentage.

2.2.6.3 c

the soil cover factor (c) slows decomposition if growing plants are present. In earlier version of the model this factor is called the “retainment factor”.

- If soil is vegetated c= 0.6;

- If soil is bare c= 1.0.

2.2.6.4 k

The decomposition rate constants (k), in years^{-1}, for each compartment are set at:

- $k_{(DPM)} = 10.0$
- $k_{(RPM)} = 0.3$
- $k_{(BIO)} = 0.66$
- $k_{(HUM)} = 0.02$

2.2.7 Mass balance equation for each compartment

After analysing the inputs and outputs for each active compartment, we can write the mass balance equations for every compartment. The general form of the mass balance equation is shown in Equation 1.

2.2.7.1 Decomposable plant material

$$DPM_{(i)} = DPM_{(i-1)} + Plant\ residues / \frac{1}{(DPM/RPM)+1} + 0.49 * FYM \ - DPM_{(i-1)} * exp^{-abck_{(DPM)}t} \ (21)$$

2.2.7.2 Resistant plant material (RPM)

$$RPM_{(i)} = RPM_{(i-1)} + \frac{Plant\ residues}{(DPM/RPM)+1} + 0.49 * FYM \ - RPM_{(i-1)} * exp^{-abck_{(RPM)}t} \ (22)$$

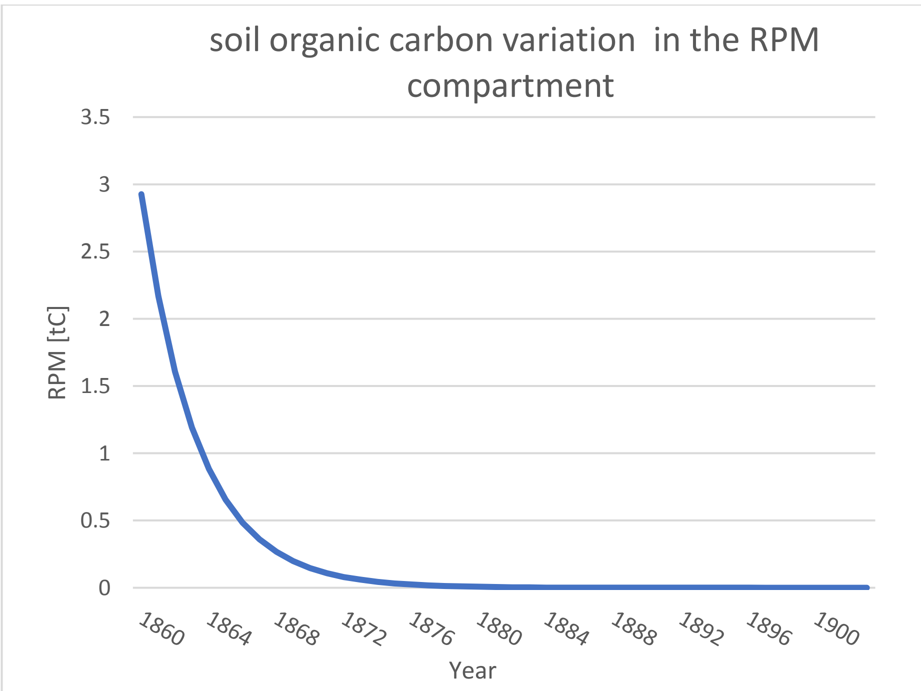

Figure 9: Annual variation of the carbon content within the RPM (resistant plant material) stock. In the first 5 years there is a sharp decline in the carbon content, then tending to 0 in the following years. The data shown in the graph are related to an experiment conducted in the fields of Rothamsted.

2.2.7.3 Humified organic matter

$$HUM_{(i)} = HUM_{(i-1)} + 0.02 * FYM + HUM_{DPMi} + HUM_{RPMi} + HUM_{BIOi} + HUM_{HUMi} - HUM_{(i-1)} * exp^{-abck_{(HUM)}t} \quad (23)$$

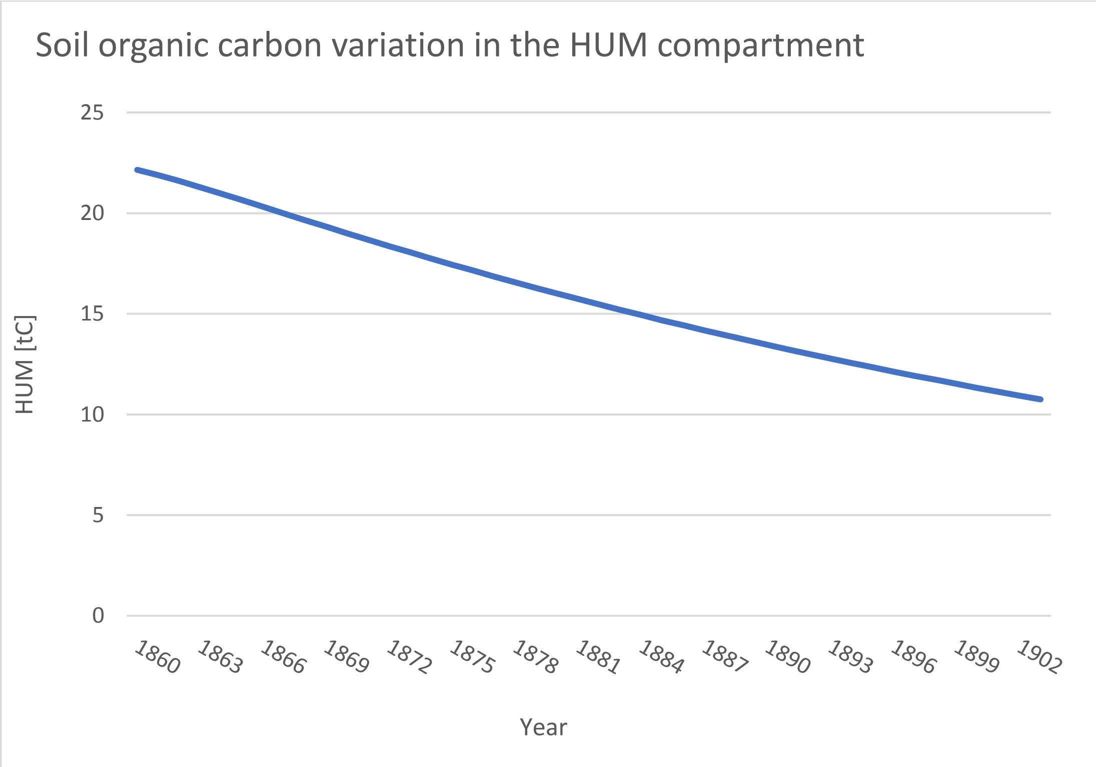

Figure 10: annual carbon change in the HUM stock. The data shown in the graph are related to an experiment conducted in the fields of Rothamsted.

2.2.7.4 Microbial biomass (BIO)

$$BIO_i = BIO_{i-1} + BIO_{DPMi} + BIO_{RPMi} + BIO_{HUMi} + BIO_{BIOi} - BIO_{i-1} * exp^{-abckt} \quad (24)$$

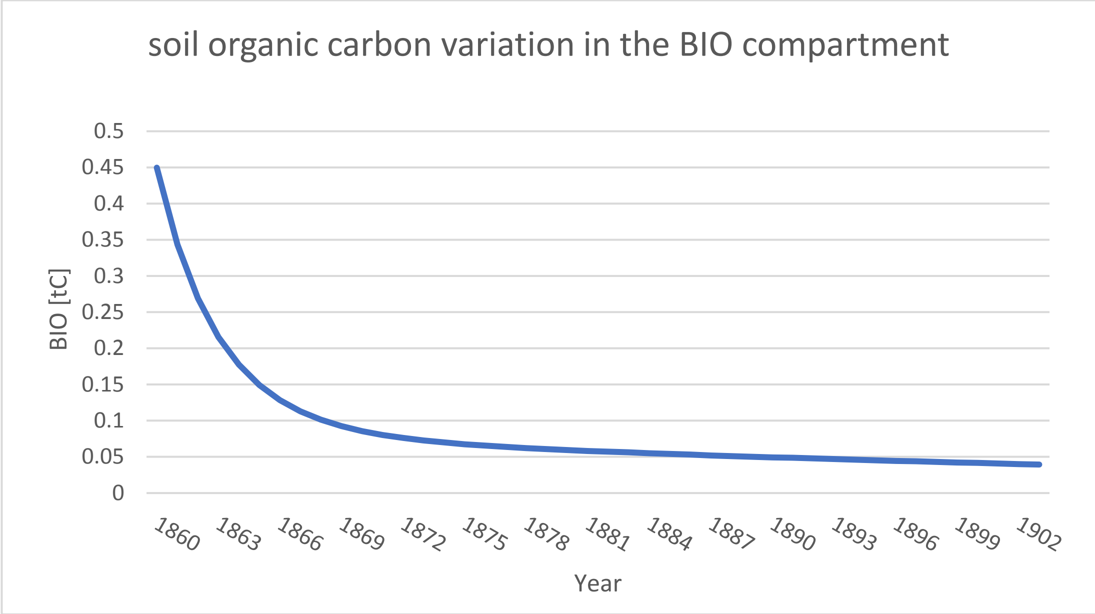

Figure 11: annual change in carbon in the BIO stock. It shows a similar trend to that described for the RPM stock. The data shown in the graph are related to an experiment conducted in the fields of Rothamsted.

2.2.8 CO_2

The CO_2 compartment becomes part of the model but behaves differently than the four active compartments. It forms from the degradation of the other compartments. Compared to active compartments, CO_2 does not degrade but leaves the system.

$$CO_{2\,i} = CO_{2(i-1)} + CO_{2\,(DPM,RPM,BIO,HUM)i} \quad (25)$$

Equations 25, 26, 27, 28 represent the CO_2 inputs according to the DPM, RPM, BIO and HUM compartments

$$CO_{2_{DPMi}} = \frac{DPM_{i-1} * e^{-abck(DPM)^t}}{\left(\frac{1}{\left(\frac{CO_2}{BIO+HUM}\right)}+1\right)} \quad (26)$$

$$CO_{2_{RPMi}} = \frac{RPM_{i-1} * e^{-abck(RPM)^t}}{\left(\frac{1}{\left(\frac{CO_2}{BIO+HUM}\right)}+1\right)} \quad (27)$$

$$CO_{2_{HUMi}} = \frac{HUM_{i-1} * e^{-abck(HUM)^t}}{\left(\frac{1}{\left(\frac{CO_2}{BIO+HUM}\right)}+1\right)} \quad (28)$$

$$CO_{2_{BIOi}} = \frac{BIO_{i-1} * e^{-abck_{(BIO)}t}}{(\frac{1}{\left(\frac{CO_2}{BIO+HUM}\right)}+1)} \quad (29)$$

2.3 Dynamic modeling

The RothC model approach was implemented with the System Dynamics approach to model the SOC cycle for a hypothetical soil in Ravenna. System Dynamics is an approach to the study of the behaviour of the systems and, in particular, of the socio-economic systems, in which the role of the intertwining of policies, decision-making structures and temporal delays in influencing the dynamic phenomena is emphasized (system dynamics.it). The dynamics of the systems was founded in the 50s by J.W. Forrester, professor at MIT (Massachusetts institute of technology), in Cambridge (Wikipedia.org). Sterman (2000) defines system dynamics as follows: "*System dynamics is a method to enhance learning in complex systems. Just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulators, often computer simulation models, to help us learn about the dynamic complexity, understand the sources of policy resistance, and design more effective policies* ".

A dynamic system is based on two fundamental components: the stock variables and the flow variables. A stock is a quantity which is measurable at a particular point of time, and which accumulates in time, but that is defined by a quantity (e.g. the temperature of an object, in °C). A flow is a quantity that is measured with reference to a period of time and has the time dimension (e.g. the flow of temperature to an object in °C/s).

Figure 11 represents the model developed for this study.

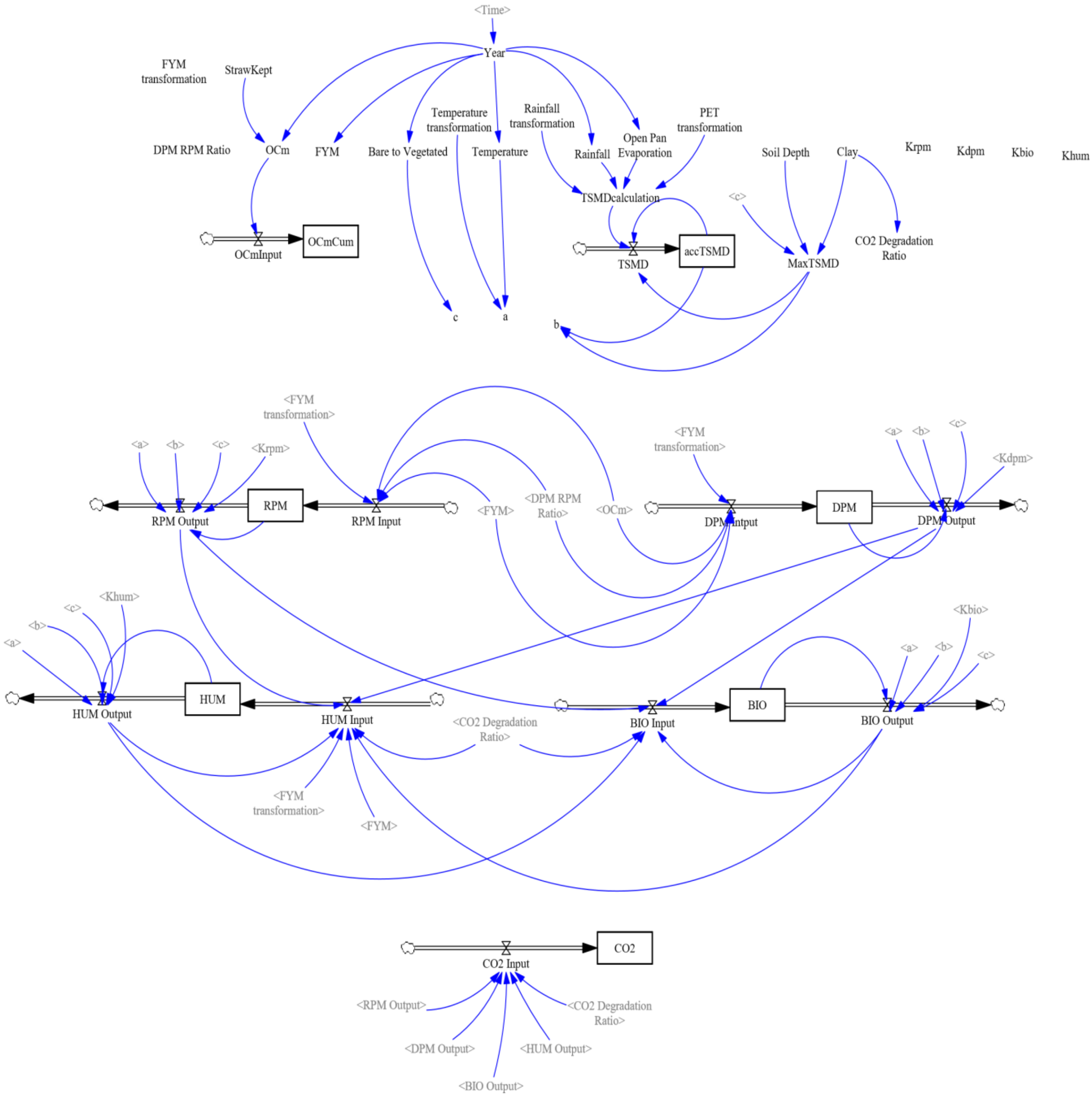

Figure 12: Schematics of the dynamic model developed for the case study.

In the model developed, we have 5 stocks: DPM, RPM, BIO, HUM and CO_2. The DPM, RPM, BIO, HUM stocks have an input flow and an output flow each (e.g. DPM input, BIO outuput etc.). CO_2, unlike the other 4 stocks, presents only inflows. This is due to the fact that CO_2, unlike other stocks, exits the system at the end of each time step.

In the RothC model, in addition to the compartments described above, we have a small amount of inert organic matter (IOM). The IOM compartment is resistant to decomposition and is used by the RothC model mainly for the radiocarbon analysis and in its inverse mode. Since we are interested in the decomposition of agricultural residues and in the forward mode only, it was not considered in the model development.

In addition to stocks and flows, the model presents variables that will influence the behaviour at each time-step of the latter. More precisely, these variables are the decomposition rates a, b, c, k (see paragraph rate decomposition) and the inputs that the RothC model requires to run (see paragraph 2.2.2).

2.4 The software modeler: Vensim

VENSIM is one of several commercially available programs that facilitate the development of continuous simulation models known as system dynamics models.

Beginning in 1988, the Vensim language and the support system were ported to the C language, since 1996 it supporte true Monte-Carlo sensitivity simulations of models. In 1996 a configuration of Vensim called Vensim Personal Learning Edition was released. Vensim PLE was made available without charge for users in education and for individuals engaged in personal (non-commercial) learning of system dynamics. Since Version 3.0, it included the Vensim Model Reader, and a Vensim DLL that can be linked with other programming languages, including C, C++, Visual Basic, Delphi, and others.

The Personal Learning Edition (PLE) of VENSIM was obtained from the www.VENSIM.com web site. It is based on C and C++ language.

2.5 Simulations

2.5.1 Simulation - Phase 1

The first simulation on the Vensim model was carried out to obtain the values of organic carbon stock at equilibrium for the compartments BIO, HUM, DPM and RPM, in the Ravenna area (climate and soil conditions) and for wheat cultivation with no straws left on the field. This means that the climatic inputs were set as in Table 1 through the use of look-up tables in the developed model, the soil inputs were set as in Table 2 and the crop and land use practices as in Table 3

clay %	soil depth
30	30

Table 2: soil input for baseline simulations on Vensim.

DPM/RPM	FYM	Ocm	bare soil to vegetated soil	month
1.27	0	0	0.6	january
1.27	0	0	0.6	february
1.27	0	0	0.6	march
1.27	0	0	0.6	april
1.27	0	0	0.6	may
1.27	0	1.8	0.6	june
1.27	1.5	0	1	july
1.27	0	0	1	august
1.27	0	0	1	september
1.27	0	0	1	october
1.27	0	0	1	november
1.27	0	0	0.6	december

Table 3: crop and land use input for baseline simulation on Vensim. FYM and OCm in tC/month.

Then, the model was run for 1000 years in order to achieve balance for the stocks mentioned above. At the beginning of the simulation (timestep 0), all the stocks were set with no organic carbon (0 tC). The value c described in section 2.2.6.3 has been set on the grain cycle and in particular with reference to the sowing and harvesting periods, November for sowing and June for harvest (see Table 3).

The DPM / RPM value was calculated using the cellulose and lignin values obtained from the study of Plazonic et al. (2016). Specifically, for straw we have a 31.47% *α-cellulose* and a 24.66 ± 1.63% of *Klason lignin*. The ratio of the two materials is 1.27 as shown in Table 3The total value of OCm includes the part of wheat straw and wheat roots calculated with Equations 30 and 31 (Kong et al., 2005).

$$wheat\ straw\ [tC/ha] = 1.06 * GDW + 0{,}39 \quad (30)$$

$$wheat\ roots\ [tC/ha] = 0{,}22 * AGB \quad (31)$$

GDW (Equation 30) is the Grain Dry Weight and the value for wheat has been extrapolated from FAOSTAT dataset, in particular the value of wheat yield in Italy for the year 2017 has been taken. AGB (Equation 31) is the above ground biomass and the value is given by the sum of straw and GDW mass. Using Equations 30 and 31, we obtain 4.4 tC of wheat straw and 1.8 tC of wheat roots.

While wheat straw can be extracted and fully or partially exported from the field, wheat roots cannot be extracted and exported. The exported fraction makes of the straw fraction reported in Table 5 and Figures 16, 17, 18.

DPM	0
RPM	0
BIO	0
HUM	0
Ocm	1.8
FYM	1.5
DPM/RPM	1.27

Table 4: baseline values used in the Vensim model to obtain equilibrium values. The depth of the soil is measured in cm, while the values of OCm, FYM and DPM, RPM, BIO, HUM are in tC.

2.5.2 Simulation – Phase 2

After determining the equilibrium stocks of carbon for each soil active compartment, a second set of simulations was run in order to estimate the effects of straw residues removal on SOC in the Ravenna study case. More precisely, 11 different simulations were run, each with a different amount of wheat straw material removed during harvest (june), while the amount of roots material was kept constant (Table 2).

Simulations	OCm
0	Straw + Roots
1	0.9 * Straw + Roots
2	0.8 * straw + roots
3	0.7 * straw + roots
4	0.6 * straw + roots
5	0.5 * straw + roots
6	0.4 * straw + roots
7	0.3 * straw + roots
8	0.2 * straw + roots
9	0.1 * straw + roots
10	0 * Straw + Roots

Table 5: values of OCm for each simulation, in tC.

2.5.3 Sensitivity Analysis

After the case study simulation, a sensitivity analysis was carried out in order to analyse how sensitive is the output of the model (the calculated C stored in the soil compartments) with respect to changes in the input variables (those detailed in subsection 2.2.1). The sensitivity analysis was carried out in three different ways:

- since the climatic variables are related between each others, we tested the response of the model to various climates (which means changing all climatic variable together);
- since the quantity of OCm, bare soil/vegetated, FYM and their yearly cycles depend on the type of crop, we changed the crop used for the simulation (only one test, with maize instead of wheat);
- We then tested all input variables in an OAT (Once At a Time) test.

3 Results

3.1 Straw elimination in the Ravenna case study

Figure 13 shows the change in the amount of organic carbon in the HUM compartment over a period of 1000 years (first simulation) obtained through the data shown in Tables 1 and 2. The organic carbon balance in the soil relative to the HUM compartment is reached after x years due to the very low value of $k_{(HUM)}$ = 0.02 year^{-1}. In the HUM compartment we have a larger total SOC quantity than the other compartments and this shows that the contribution of HUM is of major importance in the total SOC in the simulations carried out.

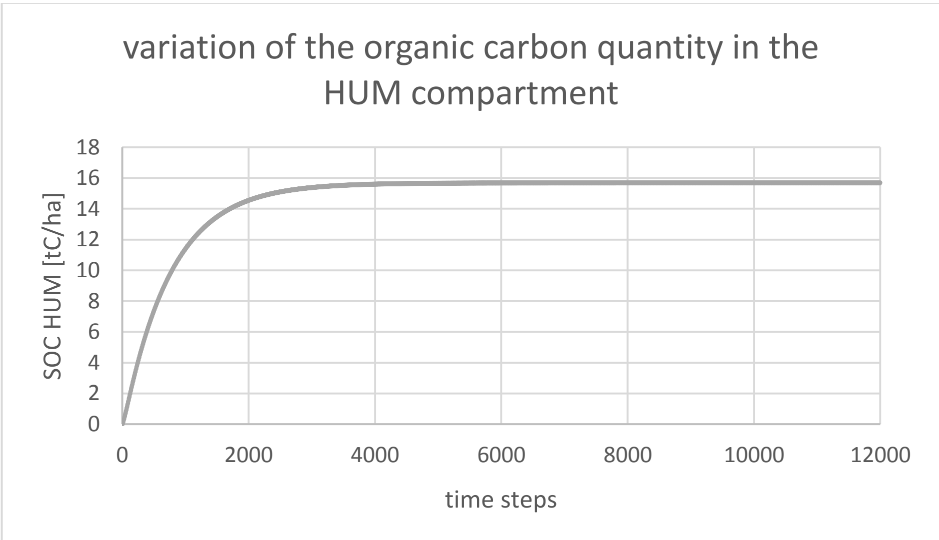

Figure 13: the graph shows the variation of the organic carbon quantity in the HUM compartment over a period of 1000 years (12,000 timesteps, 12 times steps per year) for each compartment (PHASE 1).

Figure 14 shows the variation of organic carbon for the RPM compartment. Compared to the trend for the HUM compartment described in the graph above, the balance is reached before (about 40 years) due to $k_{(RPM)}$ = 0.3 year^{-1}.

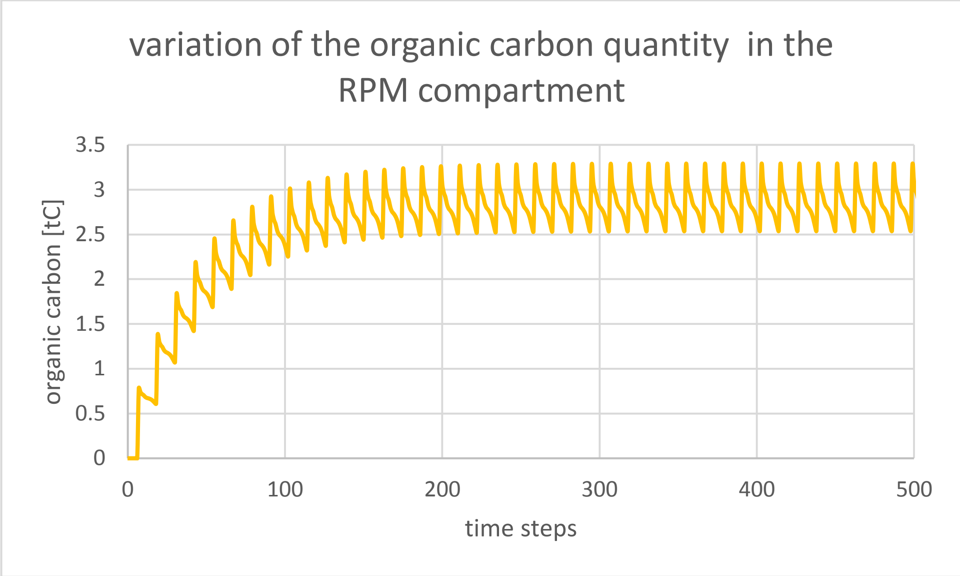

Figure 14: variation of the organic carbon quantity in the RPM compartment in the simulation to obtain equilibrium values (PHASE 1)

In figure 15, the organic carbon variations for the BIO and DPM compartments are reported. The curve for the BIO follows the same trend as the curves described for HUM and RPM. The equilibrium for the BIO compartment is reached earlier due to a slightly higher decomposition constant ($k_{(BIO)}$ = 0.66 year^{-1}) than those of HUM and RPM compartments.

The curve for the DPM compartment has a completely different trend. The equilibrium is not reached: the decomposition is so quick that the C in the DPM compartment goes quickly to almost zero after each C pulse after harvest; this is due to the very high value of the decomposition constant ($k_{(DPM)}$ = 10.0 year^{-1}).

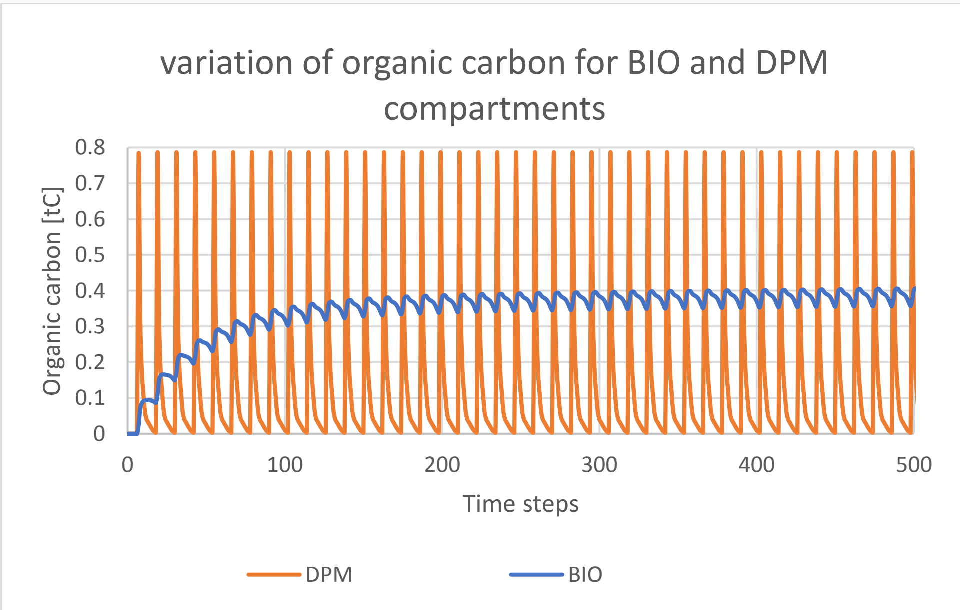

Figure 15: change in the amount of organic carbon in the DPM and BIO compartments over a period of 50 years. The different trend of the curves is due to the different decomposition constant for DPM and BIO (PHASE 1).

The amounts of carbon in the soil compartments at equilibrium were used as initial conditions for the second set of simulation, i.e. for the calculation of the effect of wheat straw removal on SOC. Table 6 shows the equilibrium values of BIO, HUM, DPM and RPM.

DPM	0.13 tC
RPM	2.8 tC
BIO	0.42 tC
HUM	15.7 tC

Table 6: input of DPM, RPM, BIO, HUM at time step 0 for the 11 simulations (PHASE 2).

Subsequently, 11 simulations were made, in which the fraction of eliminated agricultural residues was progressively increased from 0% in simulation 0 to 100% removal in simulation 10. Figures 16, 17, 18 show the change in total SOC at the tenth, twentieth and hundredth year depending on the different fraction of agricultural residues eliminated from the field. The maximum SOC, 31.1 tC occurs at 0% of agricultural residues eliminated while the minimum, 19.1 tC is found at 100% of agricultural residues eliminated from the field. The trend of the change in SOC is linear.

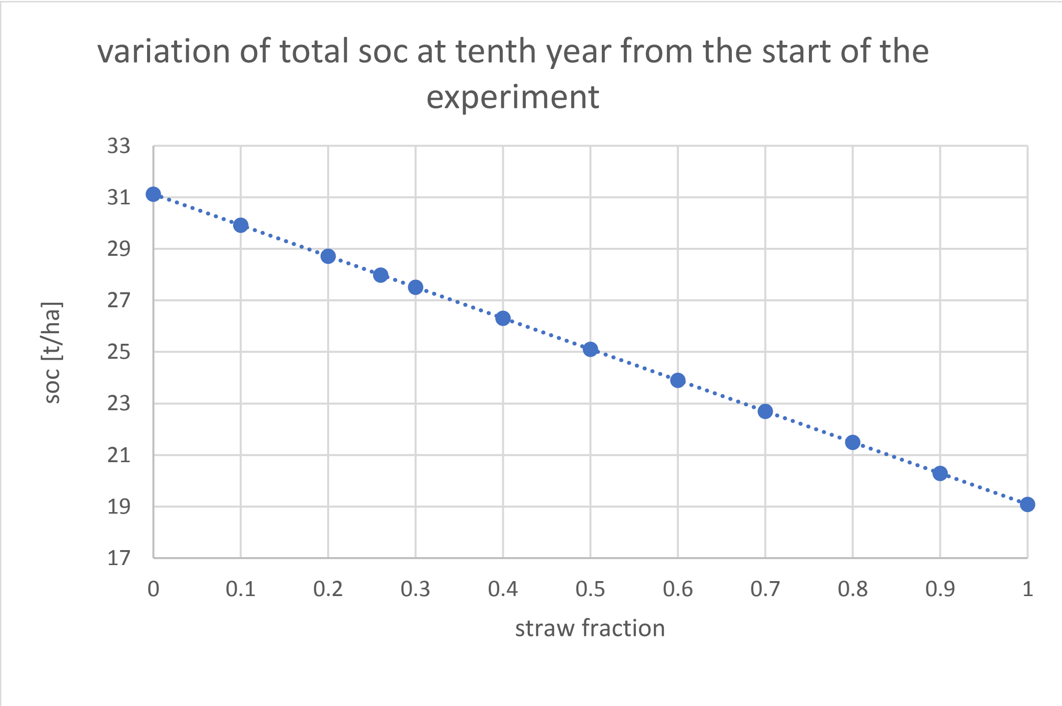

Figure 16: change in the total amount of soil organic carbon (SOC) after 10 years of simulation, depending on the amount of agricultural residues extracted from the soil (PHASE 2). The value 0 corresponds to 100% of the residues left in the ground, while 1 corresponds to the total extraction of the residues from the ground. The values in the graph are relative

to the values obtained in the simulations of the model built on Vensim. The values between 0.2 and 0.3 refers to straw sustainable as defined in Weiser et al., (2014) (see section 5).

After 20 years, the total SOC varies linearly with the increase in the amount of residues removed from the soil and a total exploitation of the residues leads to a reduction of 17tC compared to the complete release of residues in the soil.

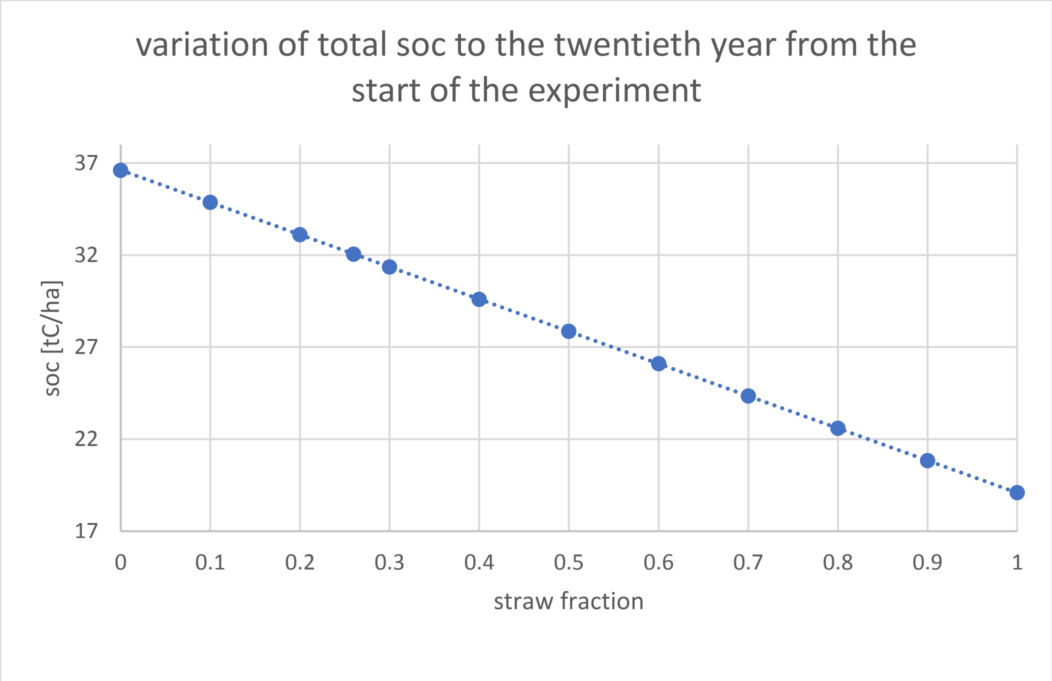

Figure 17: change in the total amount of soil organic carbon (SOC) after 20 years of simulation, depending on the amount of agricultural residues extracted from the soil (PHASE 2). The value 0 corresponds to 100% of the residues left in the ground, while 1 corresponds to the total extraction of the residues from the ground. The values in the graph are relative to the values obtained in the simulations of the model built on Vensim.

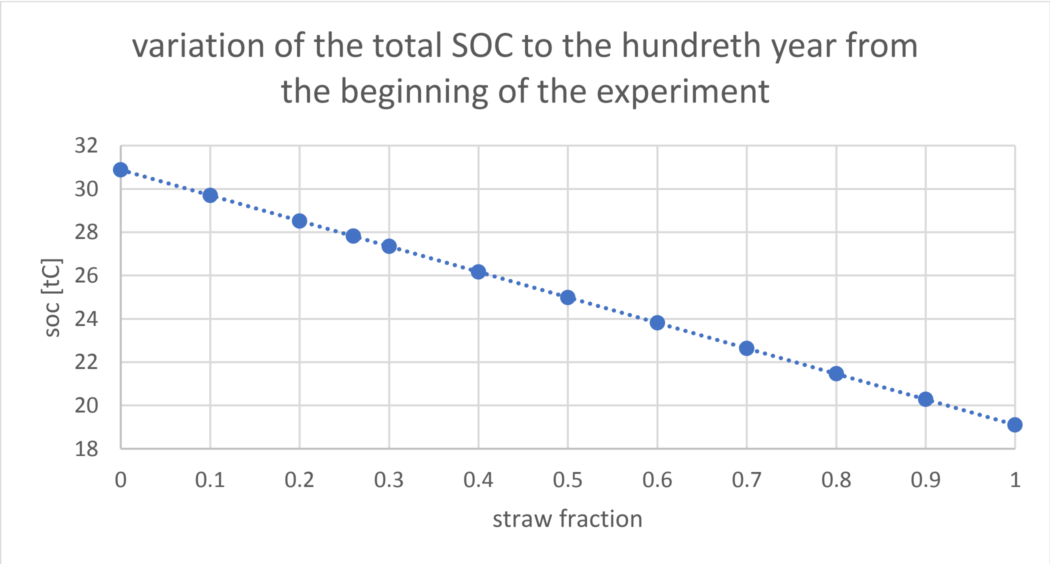

Figure 18: change in the total amount of soil organic carbon (SOC) after 100 years of simulation, depending on the amount of agricultural residues extracted from the soil (PHASE 2). The value 0 corresponds to 100% of the residues left in the ground, while 1 corresponds to the total extraction of the residues from the ground. The values in the graph are relative to the values obtained in the simulations of the model built on Vensim.

Figure 19 shows the variation in the amount of CO_2 according to the different fractions of agricultural residues extracted from the soil over a period of 1000 years. Each line represents a variation depending on the different fraction of residues eliminated. In the tenth year, we have a CO_2 stock related to 100% of agricultural residues left in the ground equal to 44.5 tC while the amount of CO_2 referred to the situation in which they are extracted from the ground is 16.3 tC. The extraction of 100% of the residues reduces the amount of CO_2 by 63% compared to the stock in the situation in which the residues are not extracted. At the twentieth year from the beginning of the simulation, we have a variation of one order of magnitude in tC between the two stocks, referring to non-extraction and complete extraction. For the situation in which the residues are not extracted, we have a stock of 103.3 tC and this value is reduced to 35.1 tC when all the residues are extracted. At the hundredth year the organic carbon values for the situations described above are respectively 578.3 tC and 179.1 tC. In the twentieth year, the removal of agricultural residues reduces the quantity of CO2 by 66% compared to the total quantity in the situation in which agricultural residues are not extracted, while at the hundredth year the effect is 69%.

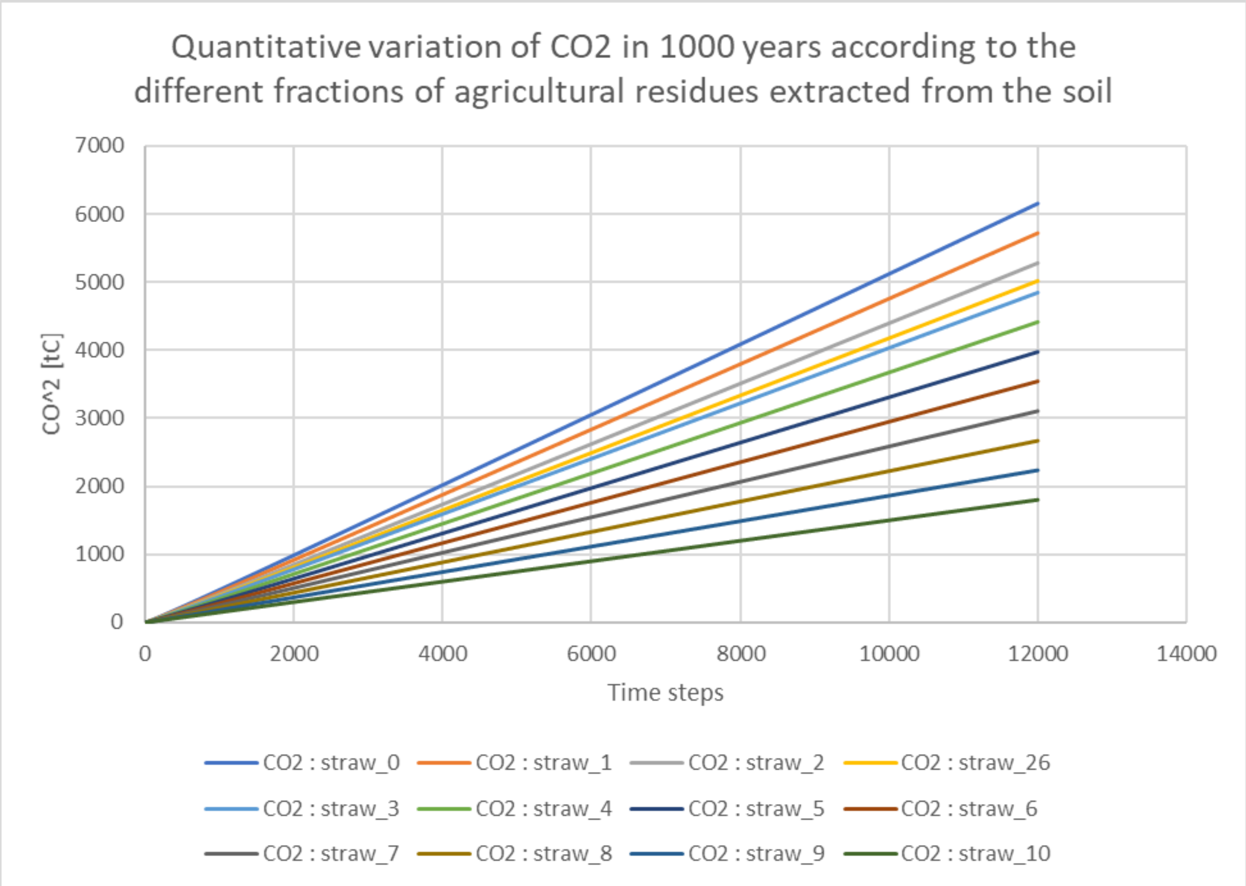

Figure 19: quantitative variation of CO_2 releases over a period of 1000 years depending on the different fractions of agricultural residues extracted from the soil. Straw 26 refers to the sustainable straw extraction from Weiser (2014).

3.2 Sensitivity analysis

In the presentation of the results below, the results for the different climates and for the OAT of the climatic inputs are shown together (subsection 3.1.1), then the two crops and the OAT of the crop-related inputs are shown together in subsection 3.1.2, finally the OAT of all the other variables are shown in subsection 3.1.3. The graphs obtained through the sensitivity analysis are shown below and discussed.

3.2.1 Climate

In Europe there are, prevalently, five classes of Köppen classified climate:

I. Semi-arid (cold) climate (most of Spain)
II. Mediterranean (Portugal, a bit of Spain, centre-south Italy, Greece)
III. Oceanic (northern Spain, France, UK, Ireland, west Germany)
IV. Humid sub-tropical (northern Italy)

V. Humid continental (southern Scandinavia, east Germany, east Europe)

We selected some sites representative of these climatic conditions (selection criteria: data availability, direct knowledge from experience, representativeness), respectively:

I. Toledo (Spain)
II. Rome (Italy)
III. London (UK)
IV. Ravenna (Italy)
V. Kiev (Ukraine)

For each of these locations, data on air temperature, precipitations and incoming solar radiation was collected and used to compute the potential evapotranspiration using Hargreaves formula (*Hargreaves and Samani*, *1985*). All other inputs to the model were kept as in the main simulation as in Table 2.

Figure 20 shows the different quantities of total average soil organic carbon (SOC) per year in the equilibrium condition (after 1000 years) for the different types of climate mentioned above. For the semi-arid climate, we have a total SOC value of 65 tC; for the Mediterranean climate 31 tC, for the subtropical humid climate 37 tC, for the oceanic climate 47 tC and for the humid continental climate 58 tC.

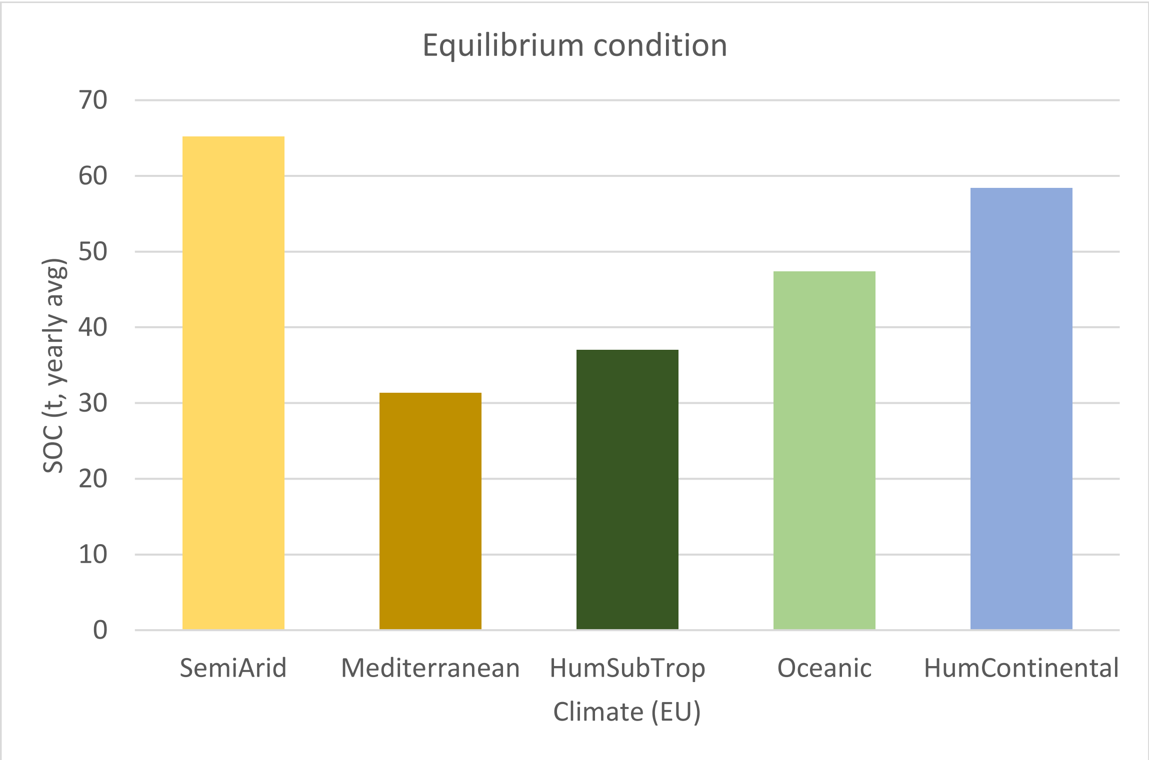

Figure 20: the graph shows the variation in the average annual quantity of total organic carbon soil, in conditions of equilibrium, according to the different climatic regimes. The semi-arid, Mediterranean, humid subtropical, oceanic and humid continental climate are reported.

Figure 21 shows the SOC after 20 years of simulation for the five climates described above. The initial conditions for BIO, HUM, DPM and RPM where of 0 tC. After 20 years, for the semi-arid climate we have a total annual average organic soil carbon amount of 18 tC, for the Mediterranean climate of 13 tC, for the subtropical humid climate of 14 tC, for the oceanic climate of 16 tC and for the humid climate continental of 17 tC.

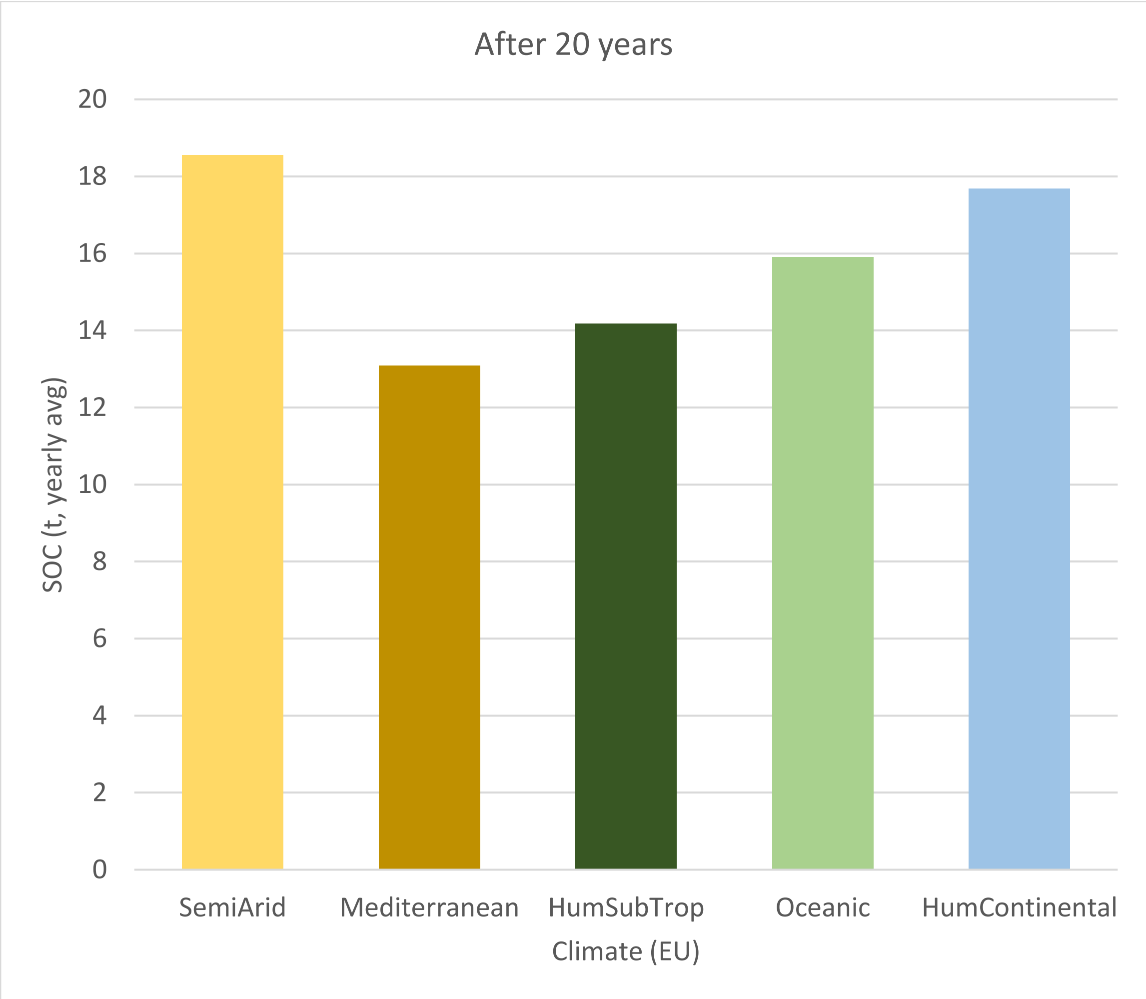

Figure 21: the graph shows the variation in the average annual quantity of total organic carbon soil, in conditions of equilibrium, according to the different climatic regimes. The semi-arid, Mediterranean, humid subtropical, oceanic and humid continental climate are reported.

Figure 22 shows the variation of the total SOC content as a function of average yearly temperature. Around the base value, the total amount of SOC does not show significant changes. For lower temperatures of the baseline there is a greater variation in the total amount of SOC while for temperatures higher than the baseline value (red dot), the variation in the amount of total organic carbon. The total value of total SOC (349 tC) occurs at a temperature of 0°C while the minimum value of total SOC (10.35 tC) occurs at a temperature of 50°C. Figures 23 and 24 shows similar relationships for the yearly average rainfall (P) and potential evapotranspiration (PET).

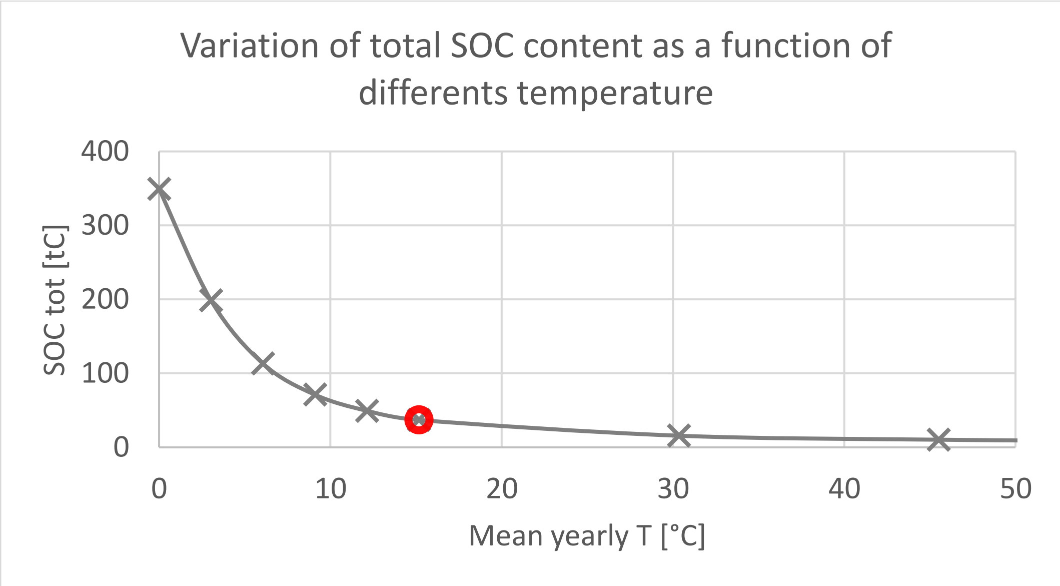

Figure 22: variation of total SOC content as a function of average yearly temperature. The red dot refers to the average annual baseline temperature of the developed model. The red dot refers to the average annual temperature of the dataset used as a baseline in the study.

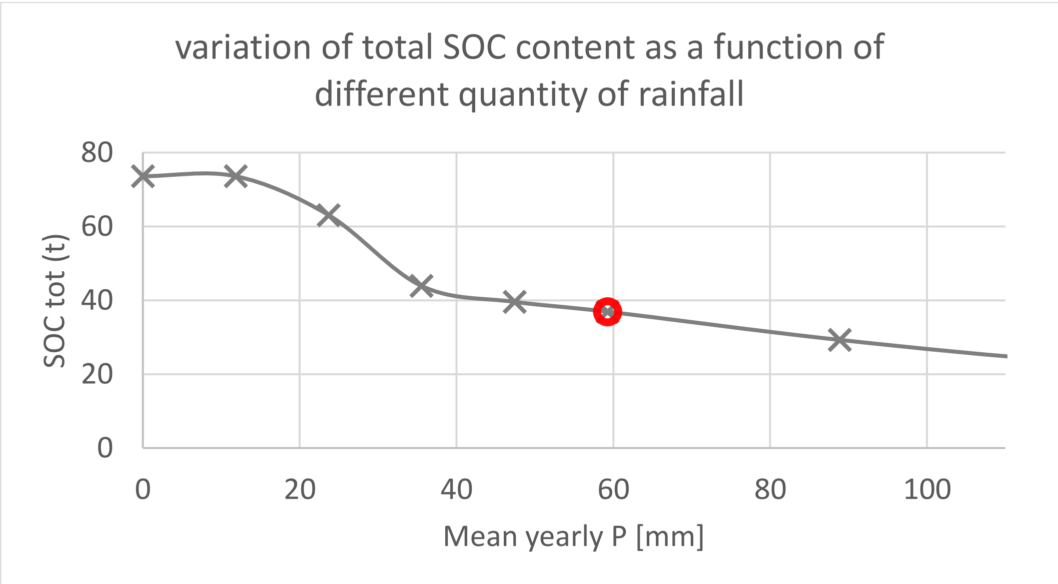

Figure 23: variation of total SOC content as a function of quantity of rainfall P [mm]. The red dot refers to the average annual baseline temperature of the developed model.

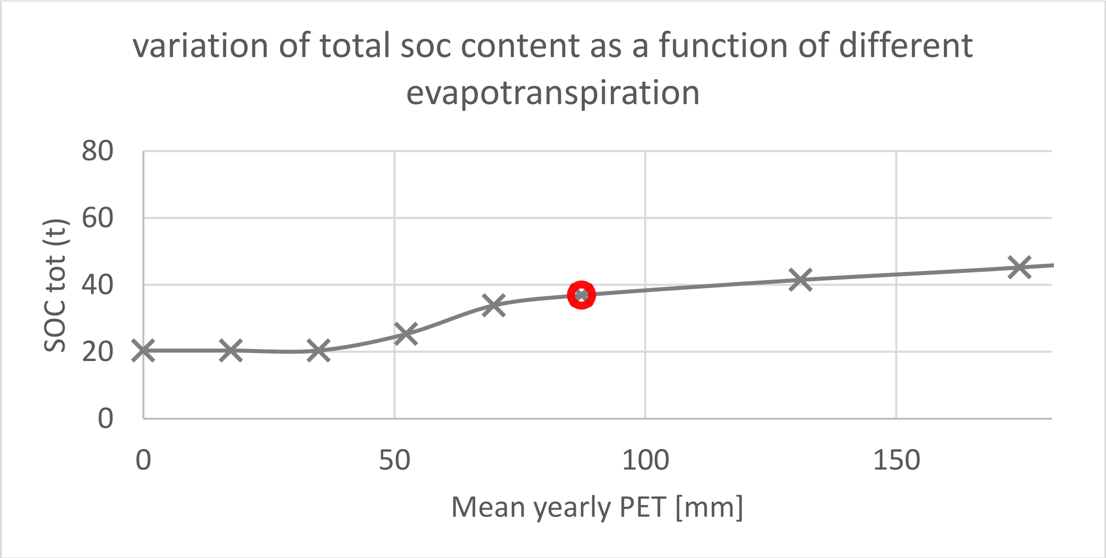

Figure 24: variation of the total SOC content according to the different values of average yearly potential evapotranspiration (PET).

3.2.2 Crops

A crop sensitivity analysis was performed to evaluate the difference between wheat and maize for the Ravenna study area. A comparison of the difference between the four simulations (wheat keeping straws on the field, wheat harvesting straws, maize keeping stovers on the field, maize harvesting stovers) is shown in Figure 25, where we have four columns for each soil compartment. Two columns refer to wheat (straw and no straw) and two to maize (stover and no stover).

For each column we have a quantitative amount of organic carbon in tonnes. It is possible to state that, in all compartments, the highest column refers to the maize cultivation with stovers kept on the field. It is also possible to see that, for the compartments BIO and DPM, the values of the columns are much smaller than the values obtained for HUM and RPM.

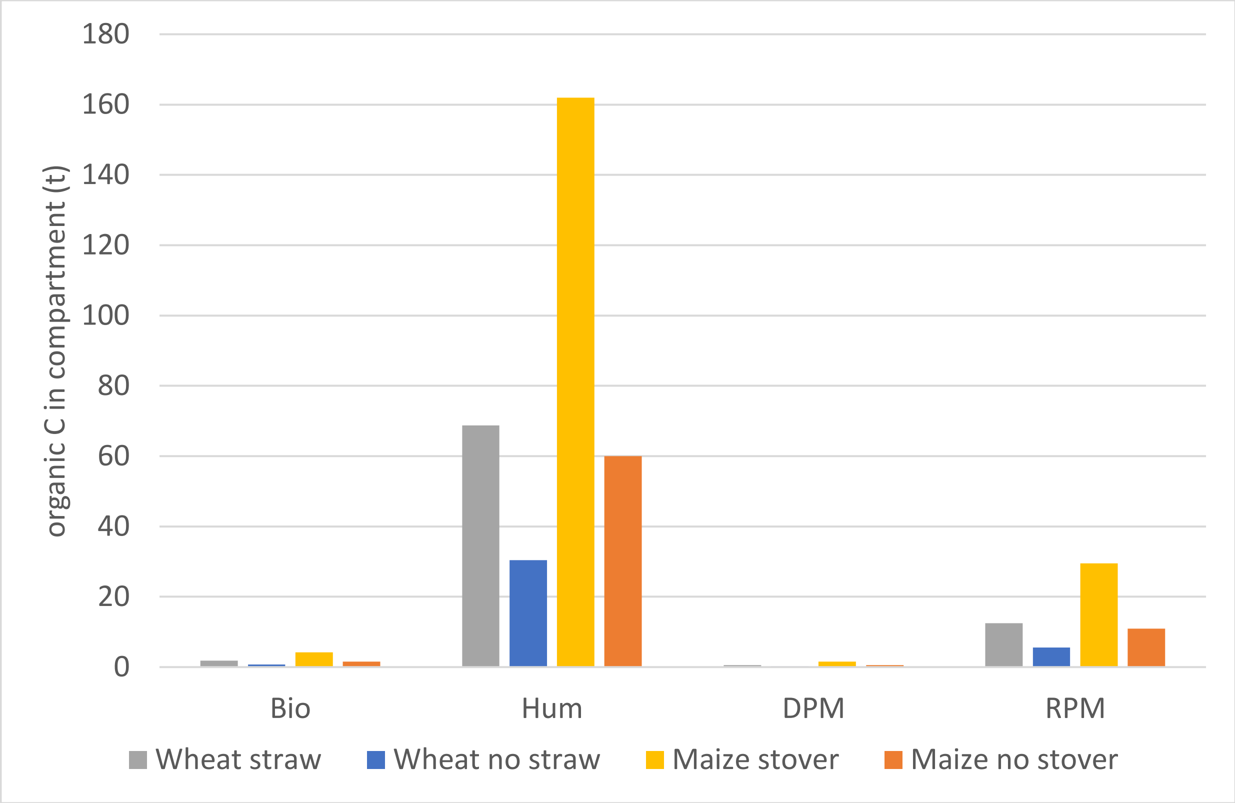

Figure 25: organic C in all compartments (BIO, HUM, DPM, RPM), at equilibrium, for wheat and maize, keeping or removing the crop residues from the field. Wheat straw, maize stover: the crop residue is kept on the field. Wheat no straw, maize no stover: the crop residue is harvested.

Figure 26 shows the total amount of soil organic carbon for wheat and maize. For wheat we have a total soil organic carbon value of 55.8 tC while for maize a total value of 62.9 tC.

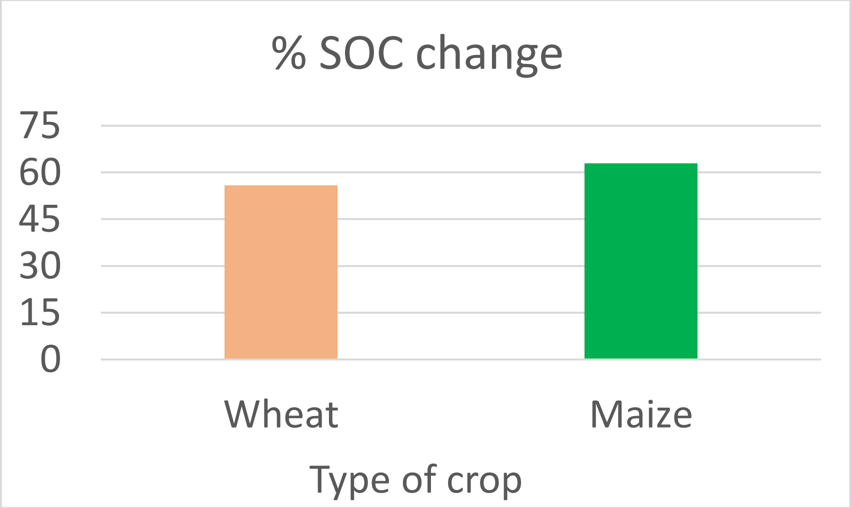

Figure 26: in the above graph, the percentages of SOC differences between residues kept on the field and residues harvested are reported for the two types of crop: wheat and maize.

3.2.3 Other variables

Figure B1 (Annex B) shows the variation of the average annual SOC in the compartments according to the different quantity of FYM entered annually in the land. The SOC values vary from a minimum of 19 tC/ha at the emission of 0 annual tC/ha of FYM, up to a maximum of 138 tC/ha at an annual intake of 10 tC/ha. The four lines shown in the graph refer each to a particular compartment. For the BIO and HUM compartments, the organic carbon values have little variation and are within a range between 0 and 1 tC (Annex A). The values of the RPM compartment have a larger range and have the highest value, 21 tC, at the point corresponding to the greater quantity of FYM introduced into the ground. The HUM compartment has a considerably larger range of values than the compartments described above and in particular ranges from a minimum of 15 tonnes corresponding to the minimum quantity of FYM up to a maximum of 113.7 tC at the maximum annual intake point of FYM in the ground.

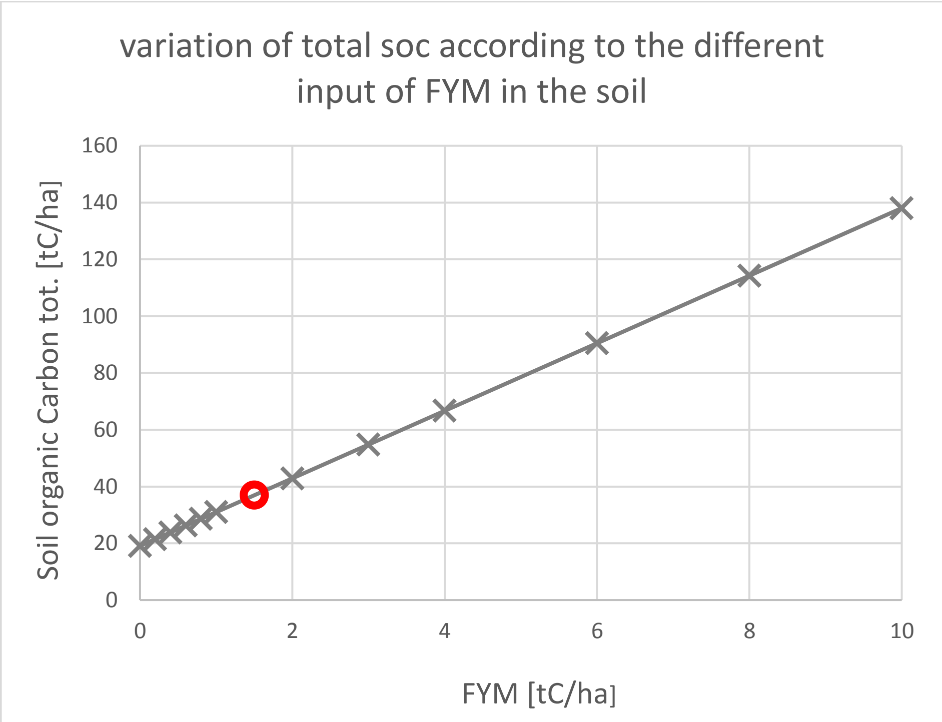

Figure 27: change in total organic carbon [tC / ha] according to the different annual quantity of FYM introduced into the soil. The red dot refers to the baseline value entered in the model.

Figure B2 (Annex B) shows the change in total SOC according to the amount of organic material placed annually in the soil. The values vary from a minimum of 19.6 tC/ha in correspondence with the minimum amount of organic material in the soil, up to a maximum of 1056 tC/ha corresponding to the maximum amount of organic material per year in the soil. For the HUM compartment, the SOC values vary from a minimum of 20 tC / ha in correspondence of the minimum amount of organic material to the soil, up to a maximum of 868 tC / ha corresponding to the maximum amount of organic material (100 tC / ha). For the RPM compartment, SOC values vary from a minimum of 3 tC / ha up to a maximum of 157 tC / ha. For the two remaining compartments, BIO and DPM, the range of values is lower than the compartments described above. For the BIO, the variation ranges from a minimum of 2 tons up to a maximum of 20 tons. For the DPM compartment, the maximum value reaches 7 tC / ha at the maximum annual contribution of organic material (see Annex A).

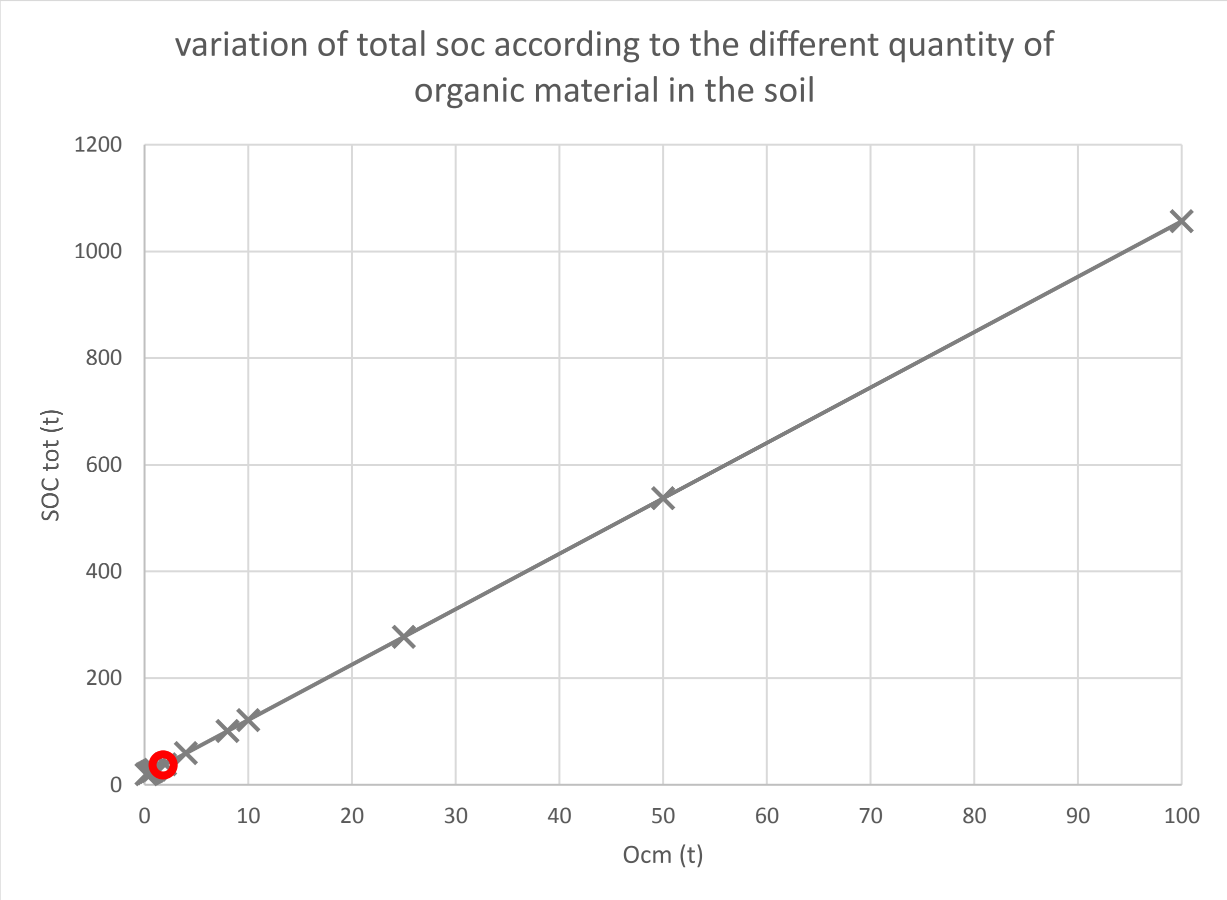

Figure 28: variation of total organic carbon as a function of the different amount of organic material in tC / ha released annually into the soil. The red dot refers to the baseline condition.

Figure B3 (Annex B) shows the average annual SOC variation for each compartment depending on the different depth of soil processing. The range of values varies from a minimum of 36.5 tC to a ground depth of 10 cm up to a maximum of 37.3 tC at a depth of 1 meter. Compared to the trends described in the above graphs, the variation in depth has a negligible influence on each compartment. If we analyse the range of values for each of them, between the minimum and the maximum SOC, there is a difference of less than 1 tC / ha. The maximum difference is in the HUM compartment where at 10 cm of depth of processing, there is a SOC value of 30.05 tC and 100 centimetres there is a value of 30.64 tC (see Annex A).

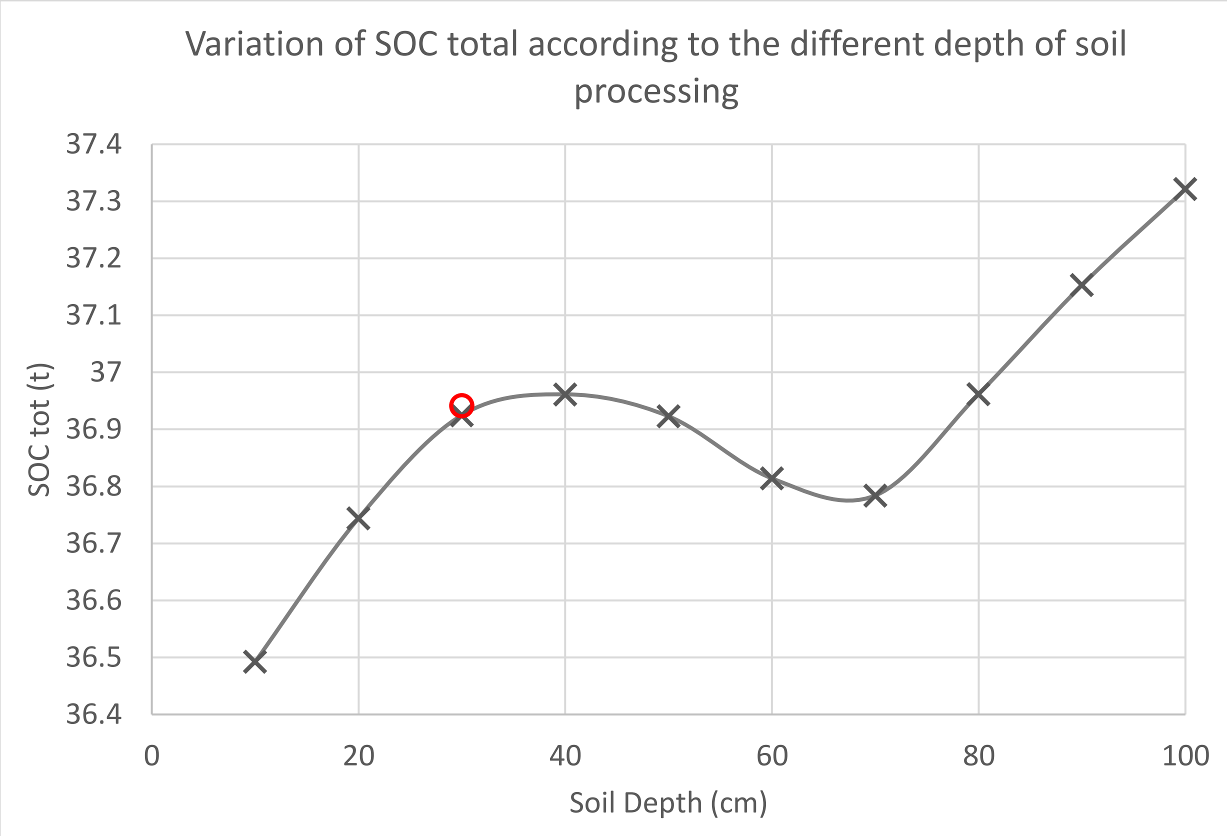

Figure 29: variation of total organic carbon soil according to the different depth of soil processing. The red dot refers to the baseline value of the model.

Figure B4 (Annex B) shows the variation of total organic carbon as a function of the different percentage of clay in the soil. In the interval between 0 and 40% of clay, we have a minimum quantity of SOC equal to 24.3 tC in correspondence of 0% of clay and a maximum of 38.2 tC in correspondence of 40% of clay in the soil. In the interval between 40% and 100% of clay, an equilibrium is reached and in fact the maximum value of SOC is in correspondence of 100% of clay and is worth 39.3 tC. For the HUM compartment, there is a larger range of values in the first in the 0-40% range of clay. In this range, the values vary from a minimum of 18 tC corresponding to a soil with 0% of clay up to a maximum of 32 tC in correspondence of 40% of clay. From 40% to 100% there is a balance of values and in fact the value of SOC changes in a negligible way, reaching a maximum of 32.7 tC in correspondence of 100% of clay. For the other three compartments, the average annual SOC value changes negligibly. Specifically, for the RPM compartment it goes from a minimum of 5.45 tC to a maximum of 5.52 tC. For the DPM compartment there is a minimum of 0.231 tC and a maximum of 0.235 tC. Finally, for the BIO compartment, it goes from a minimum of 0.80 tC up to a maximum of 0.83 tC (see Annex A).

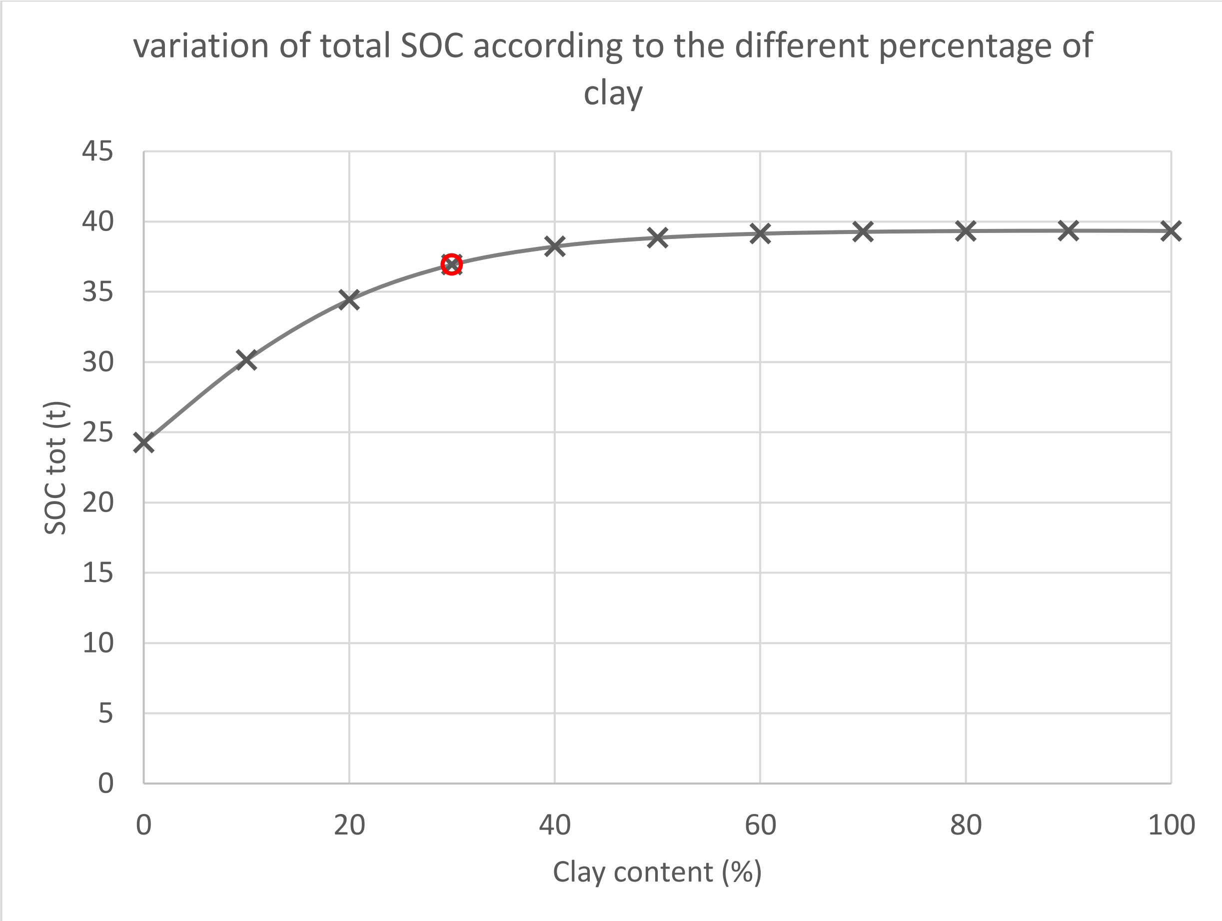

Figure 30: variation of total soil organic carbon according to the different percentage of clay in the soil. The red dot refers to the baseline value of the model.

Figure 31 shows the variation of the total SOC quantity as a function of different decomposition constant values for the RPM compartment (kRPM). The maximum total SOC value, 1019 tC, is at a $k_{(RPM)}$ = 0.001 years^{-1}. In the range of $k_{(RPM)}$ between 0.1 and 10 years^{-1} has reached a balance in the total amount of SOC. The minimum total SOC value of 31.6 tC is at a $k_{(RPM)}$ = 10 years^{-1}.

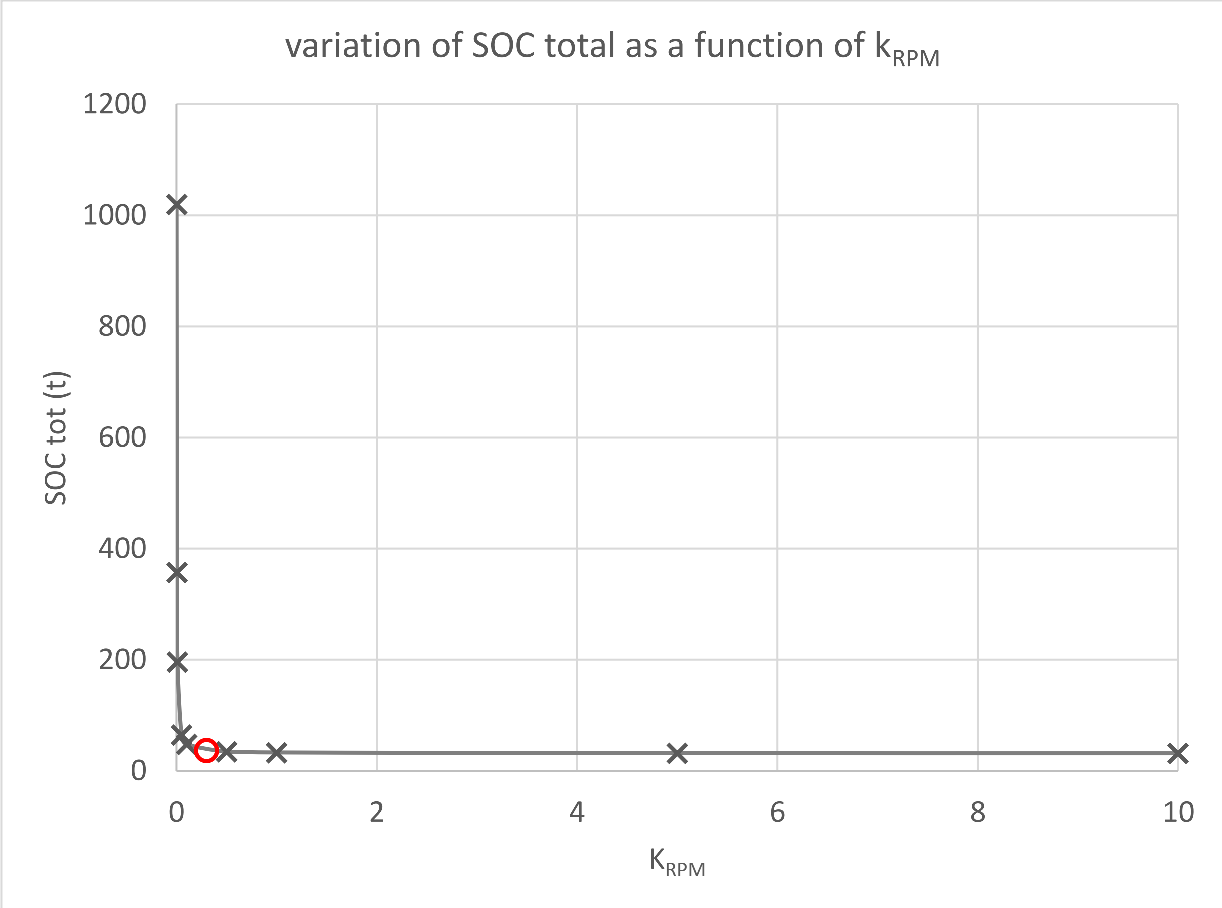

Figure 31: variation of total soil organic carbon according to the different value of k_{RPM}. The red dot (0.03 years^{-1}) refers to the baseline value of the model.

Figure 32 shows the variation of the total SOC quantity as a function of different decomposition constant values for the DPM compartment ($k_{(DPM)}$). The maximum total SOC value, 1163 tC, is at a $k_{(DPM)}$ = 0.001 years^{-1}. In the range of $k_{(DPM)}$ between 0.1 and 10 years^{-1} has reached a balance in the total amount of SOC. The minimum total SOC value of 31.6 tC is at a $k_{(DPM)}$=10 years^{-1}.

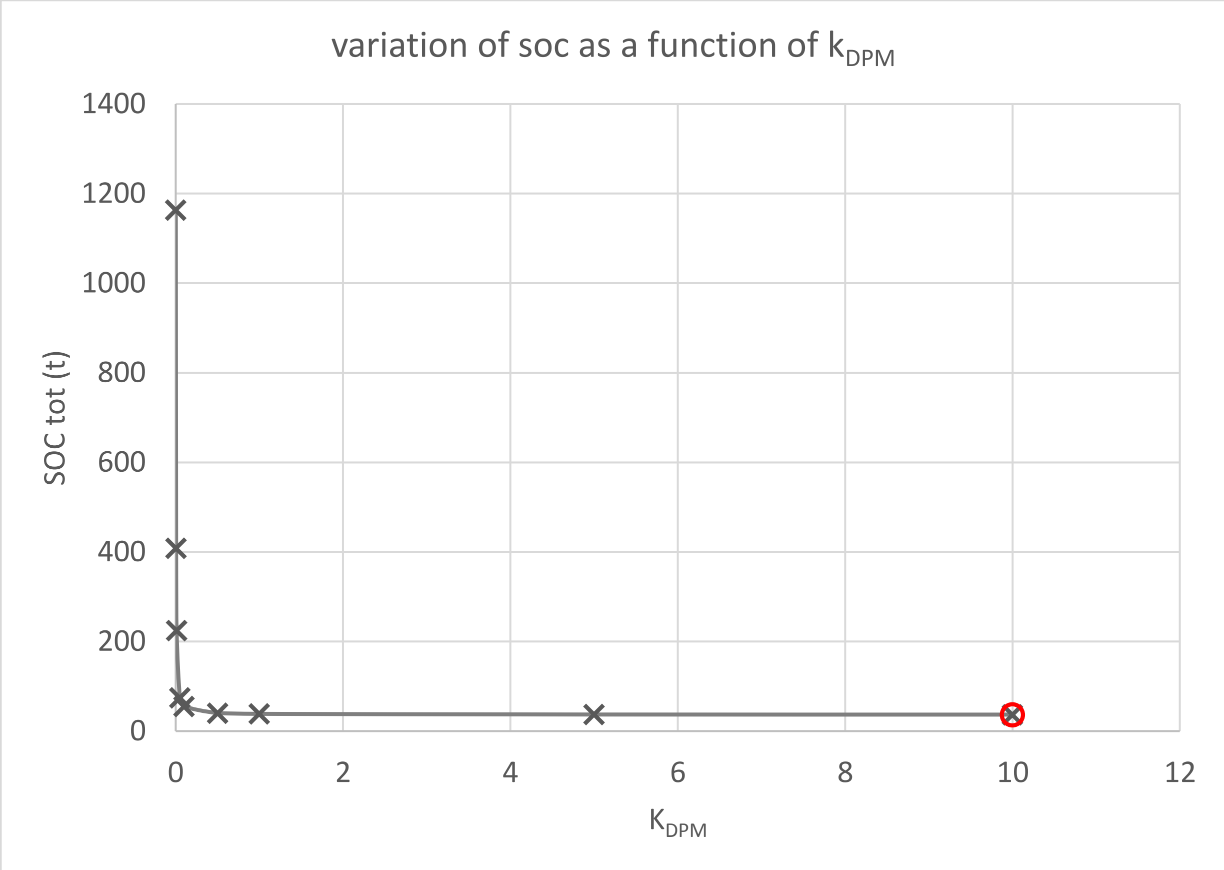

Figure 32: variation of total soil organic carbon according to the different value of k_{DPM}. The red dot (10 years^{-1}) refers to the baseline value of the model.

Figure 33 shows the variation of the total SOC quantity as a function of different decomposition constant values for the BIO compartment ($k_{(BIO)}$). The maximum total SOC value, 305 tC, is at a $k_{(BIO)}$ = 0.001 years^{-1}. In the range of $k_{(BIO)}$ between 0.1 and 10 years^{-1} has reached a balance in the total amount of SOC. The minimum total SOC value of 36.2 tC is at a $k_{(BIO)}$ =10 years^{-1}.

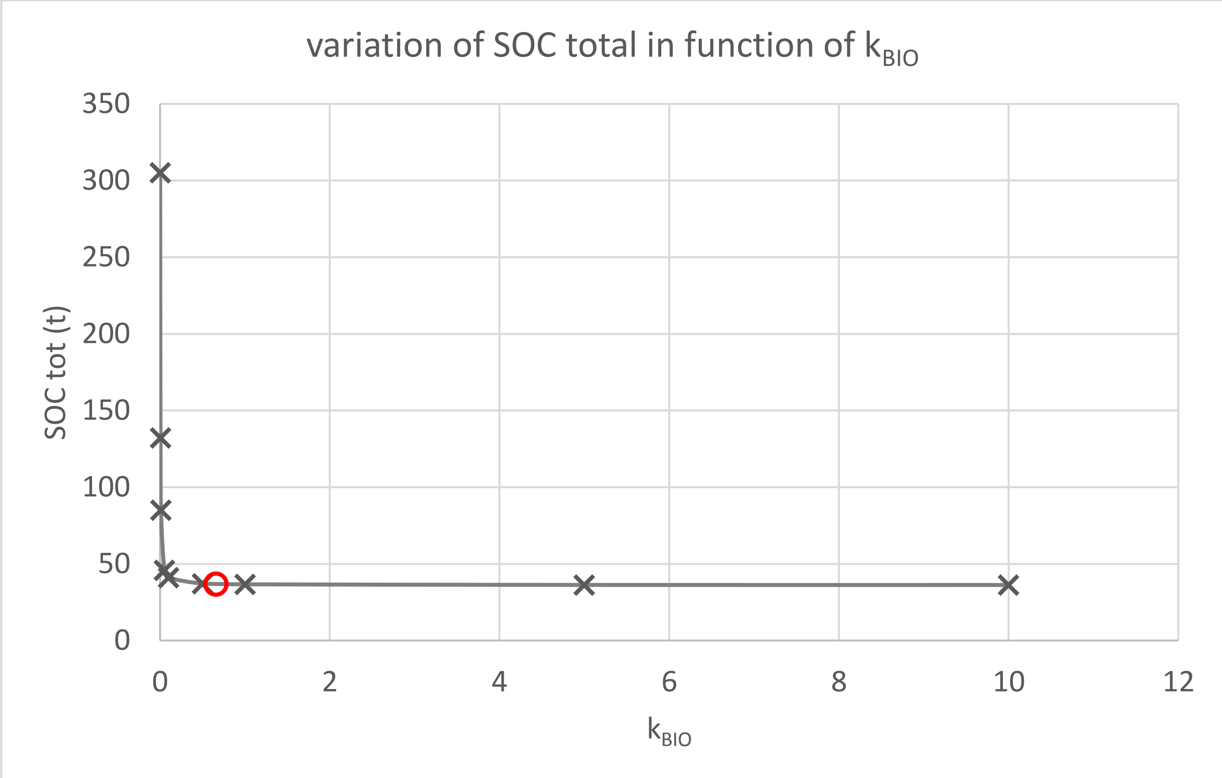

Figure 33: variation of total soil organic carbon according to the different value of k_{BIO}. The red dot (0.66 years^{-1}) refers to the baseline value of the model.

Figure 34 shows the variation of the total SOC quantity as a function of different decomposition constant values for the HUM compartment ($k_{(HUM)}$). The maximum total SOC value, 339.5 tC, is at a $k_{(HUM)}$ = 0.001 years^{-1}. In the range of kHUM between 0.1 and 10 years^{-1} has reached a balance in the total amount of SOC. The minimum total SOC value of 36.2 tC is at a $k_{(HUM)}$ =10 years^{-1}.

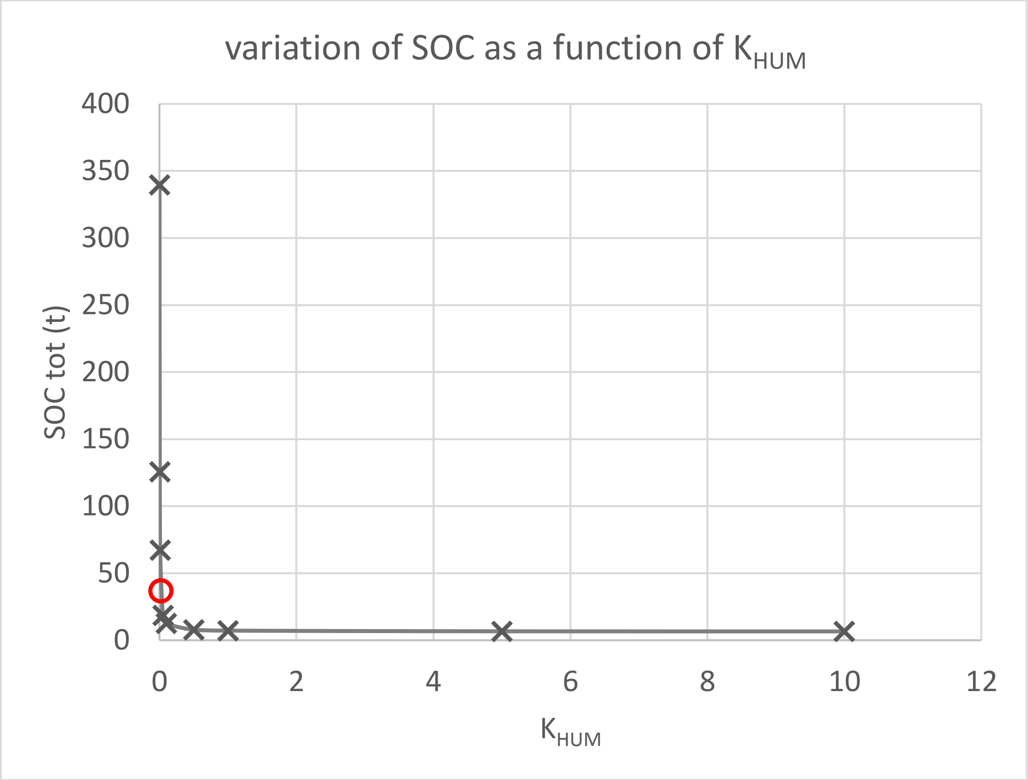

Figure 34: variation of total soil organic carbon according to the different value of k_{HUM}. The red dot (0.02 years^{-1}) refers to the baseline value of the model.

4 Discussion

4.1 Straw elimination from the field

After defining the inputs of the case study simulation, with reference to Table 5, 11 simulations were made in which the amount of residuals eliminated from the ground varied for each simulation. As an example, simulation 0 represented the non-extraction of the residues from the field, while the simulation 10 represented the total extraction of the residues from the field. Subsequently the total SOC value was calculated according to the different fractions of agricultural residues extracted at 10^{th}, 20^{th} and 100^{th} year from the beginning of the experiment. The total SOC was calculated by summing the averages of the BIO, HUM, DPM and RPM stocks for the three years specified above.

Figures 16, 17 and 18 show the results for the 10^{th}, 20^{th} and 100^{th} year, respectively. In all three cases the curve follows a linear, descending trend according to the greater quantity of extracted agricultural residues. Analysing Figure 16, it can be stated that if 100% of the residues are extracted from the soil, there is a reduction of 12 tC/ha which corresponds to an effect of 40 % with respect to the 0% extraction of agricultural residues in the soil. At the twentieth year from the beginning of the experiment, the SOC for the 0 % straw extraction is larger than at the tenth year, while the SOC for the 100 % straw extraction remained 19.1 t. This translates into a greater loss of SOC (18 tC) and an effect of 47.85 % carbon loss in case of total straw extraction. At the 100th year from the beginning of the experiment, the complete exploitation of agricultural residues leads to a loss of 12 tC and an effect of 38.1%.

The analysis on the exploitation of agricultural residues for bio-economic purposes has been the subject of many studies in recent years and the results obtained through the model developed are similar to those reported in the literature (Blanco-Canqui and Lal, 2009; Powlson et al., 2011; Weiser et al., 2013). First, the linear decrease in the total quantity of SOC in relation to the greater fraction of agricultural residues eliminated from the soil is confirmed in a paper by Blanco-Canqui and Lal (2009). Another confirmation of the results obtained on Figure 16, 17, 18 is given from a recent review by Powlson et al. (2011) in which, on a series of experiments, the removal of straw from small grains, mainly wheat and barley (*Hordeum vulgare L.*), reduced the quantity of SOC compared to straw incorporated in the ground.

The exploitation of agricultural residues for alternative uses (food, feed), involves a reduction in organic carbon input to the soil and consequently a lower amount of organic carbon available for the degradation and formation of soil organic carbon. This was the conclusion reached by Weiser et al., (2014) for the calculation of the wheat straw potential in Germany. Cereal straw is one of one the most relevant agriculture residues in Germany with a calculated theoretical potential of 29.8 Mt year^{-1} and a technical potential of 15 Mt year^{-1}. If soil restrictions are considered in order to maintain soil fertility, the available amounts are still significant: a sustainable straw potential of 7.97-13.25 Mt year^{-1} was determined in Germany.

Linking the reduction of SOC with soil quality is not easy and some articles have devoted themselves to this study. The studies of Priyanka and Anshumali, (2016); Ogle and Keith Paustian (2005) confirm the effectiveness of SOC as an indicator of soil quality.

4.2 Input behaviours in the RothC model

Figures 27, 28, 29, 30 show the variation in the quantity of SOC as a function of the Farm Yard Manure (FYM), Organic Carbon material (OCm), soil depth and clay. FYM is intended, in the RothC model, as the conventional fertilising input. All organic inputs in the actual agricultural practices can be made equivalent to a certain FYM amount. Analysing the curves of the variables described above, it can be stated that the FYM is the variable that has a greater effect on the RothC model on the basis of a large variation in the quantity of SOC. The variable clay has a greater effect on the RothC model in the range 0-40% while in the range 40-100% the amount of SOC reaches equilibrium and there are no effects. The soil depth variable, despite a non-linear SOC variation, does not have significant effects on the RothC model since the variation between the minimum and maximum SOC is 0.8 tC. The OCm variable has a direct effect on SOC on the RothC model, just as discussed for the FYM.

4.3 Climate

As reported by Jenny (1941), the organic carbon content of a soil depends on various factors such as climate, organisms (vegetation and fauna) and the time period examined. Climate plays an important role; plant production is low in arid climates due to low rainfall and therefore also the contributions of organic substance to the soil are lower than those of more temperate climates; furthermore, the degradation of these residues is high due to the high temperatures (Golchin et al., 1994). The presumably unrealistic value for the semi-arid climate (Figures 20) obtained from the sensitivity analysis shows a consistent overestimation by RothC of SOC in arid climates. This criticality has already been underlined by the works of Farina et al., (2013) and Lobe et al., (2005); in the latter, in a semi-arid region in South Africa, RothC required an unrealistic small input of C. In reality in semi-arid climates the low precipitation rate, the high temperatures and the reduced contribution of organic material in the soil result in a lower total SOC quantity. Probably, arid climates stretch the relationships and the processes included in the model, which, after all, was calibrated in a humid area (England).

Figure 16 shows that the lowest SOC value corresponds to the Mediterranean climate. This type of climate is characterised by seasonal dryness, and many neighbouring areas in the Mediterranean are classified as arid or semi-arid (Muñoz-Rojas et al., 2012; Albadalejo et al., 2013). In Mediterranean agricultural systems, levels of productivity are typically low and there is a large dependency on irrigation (Aguilera et al., 2013a; Ouda et al., 2016). Because of their low SOC contents, these areas are often degraded and vulnerable to environmental changes, and climate change is predicted to have a large impact upon them (Metz et al., 2007).

Analysing the values of maximum total SOC (semi-arid climate) and minimum total SOC (Mediterranean climate) in Figure 16, it can be said that the climate factor plays a very important role in the production of SOC. In quantitative terms, between the two types of climate there is a 50% effect.

4.4 Crops

The sensitivity analysis in relation to the type of cultivation was carried out by analysing the different behaviour between maize and wheat. These two types of cultivation were chosen in relation to the accessibility and accuracy of the data (Faostat), the presence of a sizable amount of crop residues, and to their global spread (197 and 218 Mha for maize and wheat, respectively).

In Figure 25 two situations related to maize and two to wheat are compared. For the maize the quantities of organic carbon in the BIO, HUM, DPM and RPM pools are compared in the stover and no stover situation, while the straw and no straw situations are analysed for the wheat. 'Maize stover' means that the residues of maize (*Zea mays L.*) plants are left in a field following the harvest of the grain, while 'maize no stover' means that the residues of maize plants are removed following the harvest. The same distinction is made for wheat, where 'straw' corresponds to the situation in which the residues are left in the soil after the harvesting period while 'no straw' corresponds to the opposite situation in which the residues are removed from the soil after the harvesting period.

For the BIO and DPM pools, the model returns negligible organic carbon values according to the four situations described above, while the highest organic carbon values are found in the HUM compartment (Figure 25). In general, the organic carbon values for the HUM compartment are much larger than the values referring to the other three compartments, as found also by Bhattacharyya et al., (2011) and Coleman and Jenkinson, (2014).

Figure 26 shows, in percentage, the total SOC difference in the same climatic conditions between the two types of crop for the two possible practices: keeping all the residue on the field or harvesting it. The amount of SOC kept on the field is larger for maize, and between the two types of crop there is a total SOC variation difference of 12.7%.

4.5 Other variables

Among the variables analysed, the one that most influences the output is the farmyard manure (FYM). Analysing Figure 27, we see a greater variation in the amount of organic carbon in the HUM and RPM compartments compared to BIO and DPM. At the level of total SOC, Figure 27, a variation of 1 tonne of manure put into the soil in a year, implies a variation of 20 tonnes of organic carbon in the soil. If the minimum and maximum SOCs corresponding to an annual manure variation of 10 tons are considered, a variation of one order of magnitude is obtained. Therefore, it is necessary to consider the right annual amount of manure in order not to overestimate the result and arrive at incorrect conclusions.

Figure 28 shows the change in the quantity of SOC according to the different quantity of organic material placed annually in the soil. For our study the residues deriving from the roots and from the wheat straw were taken as input of organic material. The red dot shown in the graph corresponds to the value used as the baseline and is the value given by the contribution of organic carbon deriving from the roots, whose value was obtained by the equation of Kong et al., (2005). Around the baseline value, a small change in annual OCm does not reflect a large variation in the quantity of SOC, the further one moves away from the value, the more the variation becomes SOC becomes significant.

The different depth of soil processing (Figure 29), involves a non-linear variation of total SOC. In the study conducted here, a worked soil depth of 30 cm was used as the baseline value. In the 0-40 cm interval there is an increase in the total SOC quantity, with a first maximum corresponding to a 40 cm worked soil profile. In the interval 40-70 cm the quantity of SOC decreases and then returns to increase in the interval 70-100 cm where it reaches the maximum total value of SOC. Despite the non-linear trend, the total SOC variation in the 0-100cm range is minimal and corresponds to only 0.8tC. In relation to what has been described, a different processing depth will affect the total SOC final result in a negligible way.

Figure 30 shows the trend of the total SOC according to the different quantity of clay% in the worked soil profile. For the model developed, a hypothetical soil was considered with 30% clay (red dot in graph 26). If the 0-40% range is considered, the total SOC value increases of ~12tC, while in the 40-100% range of clay a balance is reached in the total quantity of SOC. So, uncertainty in clay contents has a stronger effect on SOC results for soils with clay values <40% compared to soils with clay values> 40% where the effect is negligible.

4.6 Decomposition rate constants of compartments

Each compartment (DPM, RPM, BIO, HUM) contains a mass of organic carbon, defined as Y tC/ha; this amount of organic carbon declines to $Ye^{-abckt}\ tC/ha$ at the end of the month. Based on what is described in section 2.2.6 the only factor that varies for the different compartments is the decomposition rate constant k. This rate of decomposition is of major importance in the dynamics of variation of the SOC content in the various compartments and determines the time with which a compartment achieves a balance in the total SOC quantity. The impact of k on achieving equilibrium are shown in Figures 31, 32, 33 and 34. The effect of uncertainty on small (< 0.01 year^{-1}) values of k has a huge effect on SOC results, while, for values of k >0.05 year^{-1}, the effects are negligible.

Since $k_{(HUM)}$ is ~0.02 year^{-1}, a particular care should be taken in determining its exact value for the particular study case (RothC k constants were calibrated on the Rothamsted field experiment). The BIO, HUM and RPM compartments have very small decomposition rates (see the decomposition rate constant section) which results in a very slow decomposition of the organic carbon in the soil and in a long period of time to reach the SOC balance.

The DPM compartment, unlike the other pools described above, has a constant decomposition rate k of two orders of magnitude greater than those of BIO, HUM and RPM. This leads to the achievement of equilibrium in a very short period of time and explains the different trend of total organic carbon in the soil compared to the trends of the other three pools (Figure 34). In practice, the organic matter in DPM is quickly decomposed, and, therefore, there is no real “equilibrium” reached by the compartment, with the organic carbon in it that follows the periodic cycles of the crop (the organic matter input) and of the climate.

4.7 CO_2

CO_2 is generated by the degradation of the compartments BIO, HUM, DPM and RPM and, unlike the latter, it does not undergo degradation and leaves the system. Despite this, it could be taken into account to evaluate the potential effects of emissions into the atmosphere.

Analysing the results shown in Figure 19, it can be stated that the presence of agricultural residues in the soil has a significant effect on the CO_2 stock in the soil. In all three situations analysed the effect is greater than 60%. The release of agricultural residues in the soil has an effect that results in a greater capture of organic carbon within the soil and consequently a reduction of emissions into the atmosphere; the process just described is called soil carbon sequestration Priyanka and Anshumali, 2016). The exploitation of agricultural residues for biobased purposes leads to a reduction of the stock (tC) of organic carbon in the soil for the CO_2 compartment and a consequent higher emission of CO_2 into the atmosphere. Therefore, the emissions of CO_2 from decomposing organic material must be taken into account in relation to the exploitation of agricultural residues for bio-based products.

4.8 Nitrogen

The effects of residues kept or harvested from the field on the soil nitrogen was not included in this study due to time constraints. However, it is useful to, at least, discuss it, since nitrogen is directly related to soil fertility. Figure 35 shows the nitrogen cycle in the soil; the nitrogen inputs in the soil are mainly due to organic matter (R-NH2) and fertilizers.

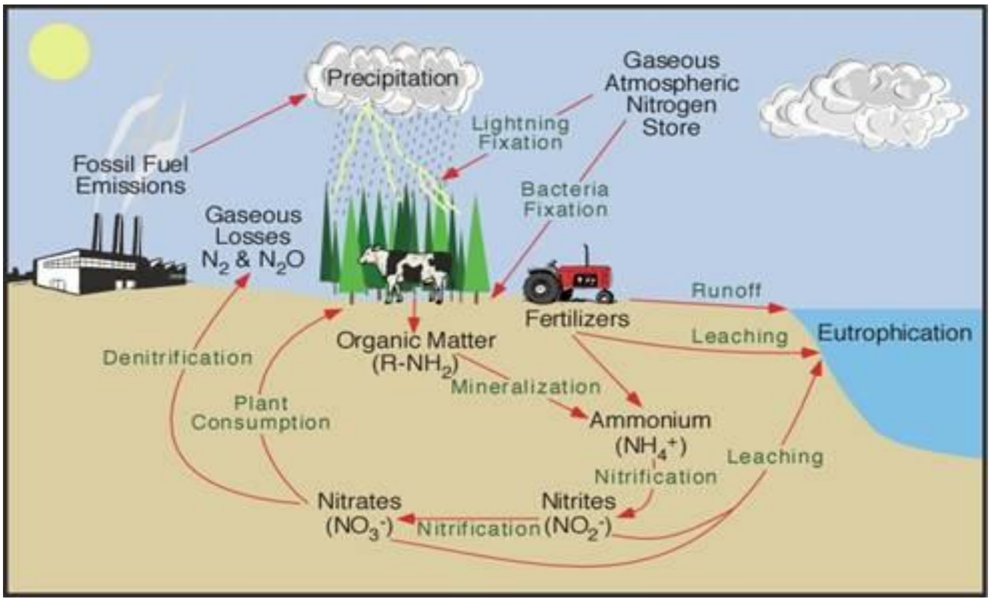

Figure 35: nitrogen cycle (source: Arpat).

The organic matter in the soil (organic nitrogen), following a process of mineralization, is transformed into mineral nitrogen (NH_4^+) and after the nitrification processes, the latter will first be transformed into nitrite and then into nitrate. The mineralization process is aided by the action of micro-organisms present in the soil that exploit the organic nitrogen present in the soil as an energy source. In the case of fertilizers, the organic nitrogen present in the soil is transformed into ammonium and then into nitrites and then into nitrates (Ercoli e Masoni, 1984). The process opposite to mineralization is the immobilization of nitrogen that occurs when residues with a low level of nitrogen are incorporated in the soil. The microorganisms using the nitrogen reserves in the soil immobilize it in more complex and stable forms that are part of their cellular composition. The consequence of this process is the reduction of the nitrogen available in the soil for the decomposition of organic matter. Nitrogen is also is eliminated through the denitrification process and due to its consumption by the plants (Ercoli e Masoni, 1984).

The C/N ratio is important in determining the fertility of the soil. The C/N ratio indicates the existing relationship, in the soil organic matrix, between organic carbon and nitrogen. The importance of this parameter lies in the fact that the microorganisms in the soil, to carry out the activity of degradation and re-elaboration of the organic substances, need 30 carbon atoms against 1 nitrogen atom. The first 20 C atoms are oxidized to CO_2 and 10 are used to form organic compounds of neogenesis. Neogenesis materials are substances of a complex nature that are less susceptible to decomposition and form humic substances (unirc.it). In the humified organic substance the C/N ratio is about 10.

Organic matrices with a high C/N ratio are poorly mineralized and actively participate in the humification process, i.e. the formation of stable humus. Also, this type of organic substance reaches the mineralization but in a progressive manner over time and is therefore to be considered an essential element of the fertility of a soil. The straw materials and in general those coming from the plant world are characterized by a high C/N ratio and consequently they undergo a very slow mineralization process, but the presence of cellulose and lignin allows the formation of a stable organic substance (Carbon to Nitrogen Ratios in Cropping Systems, USDA).

The matrices characterized by a low C/N ratio undergo a rapid mineralization process, with the release of mineral elements in an assimilable form. The organic matrices coming from the animal world are characterized by a low C/N ratio and therefore a high presence of nitrogen; they are matrices that mineralize promptly but do not participate, if not minimally, in the formation of stable humus (Carbon to Nitrogen Ratios in Cropping Systems, USDA)

The optimal conditions to which we should strive is that of a C/N ratio that expresses a substantial balance between the processes of mineralization and humification. Since nitrogen is usually added to the soil as a fertilizer, a decrease in SOC would result in an increase in nitrogen loss from the field, with an increased risk of contamination of groundwater and eutrophication of water channels (Carbon to Nitrogen Ratios in Cropping Systems, USDA)

5 Conclusion

Regarding the objective of the thesis, the RothC model was analysed and the intrinsic equations to the model were extrapolated. Subsequently, based on the RothC model, a dynamic model was developed through the Vensim software in order to estimate the effects of the extraction of wheat straw from a field on the SOC. After that, an exploratory sensitivity analysis was conducted to evaluate the influence of the input variables on the model developed.

As described in the section 3.1, 11 simulations were made, in which the fraction of agricultural residues from the ground varied. In the first simulation 100% of the agricultural residues (wheat straw + wheat roots) were left in the ground while in the last simulation only the residues deriving from the wheat roots were left in the soil. For each simulation the total organic carbon was calculated, given by the sum of the organic carbon deriving from the compartments BIO, HUM, DPM and RPM. In particular, the results were assessed at the tenth, twentieth and hundredths of the year since the beginning of the experiment (for example, for the tenth year the organic carbon averages were calculated for the four compartments at the tenth year, the same thing was done for twentieth and for the hundredth year).

In all three periods analysed there is a linear decrease of SOC with increasing fraction of residues eliminated from the ground. In the tenth year, a complete removal of residues after the harvesting period results in a 38.6% effect in terms of tC compared to the total amount of soil organic carbon in the situation where 100% of agricultural residues are left in the soil. At the twentieth year there is an effect of 47.8% while at the 100th year the effect is 38.1% (a value very similar to the effect found after 10 years).

But how do we quantify the effect of the removal of agricultural residues on soil fertility, and, therefore, evaluate amount of residues which can be extracted sustainably?

The relationship between total SOC loss and soil fertility is the subject of recent research. Studies in literature do not find a unique value valid for all situations at global level and for different types of climate. What is known is that SOC influences soil resistivity to erosion and nutrients availability. The few studies conducted to establish threshold levels for the removal of crop residues for alternative uses, particularly in the US Corn Belt region, indicate that approximately 30% -50% of the total produced stovers can be removed without causing serious negative effects on the soil (Lindstrom et al., 1979; Nelson, 2002; Kim and Dale, 2004; Graham et al., 2007).

However, these estimates are based only on residue coverage requirements for soil erosion control and do not consider residue requirements to support soil and agronomic resources and improve the environment. The threshold levels for the removal of crop residues must be established based on the residues necessary to conserve soil and water, maintain or increase crop production, increase the SOM pools, reduce net GHG emissions and minimize pollution from non-point sources (Graham et al., 2007).

In a study conducted in Germany (Weiser et al., 2014) the humus balance method was used to decide whether straws can be removed from arable land without endangering the SOM supply essential for soil fertility. The humus balance is given by Hb = Hs + Hd where Hs is the humus supply and Hd is the demand of humus.

$$Hs = \sum(S_{crop} * Y_{crop} * G_{crop} - S_t) * C_{res} + \sum A_r * C_{res} + X_w * C_{res} \quad (32)$$

$$Hd = \sum C_{crop} * S_{crop} \quad (33)$$

Where Y_{crop} is the grain yield (Mg ha^{-1}), G_{crop} is the crop specific grain to straw ratio, S_t is the straw yield, C_{res} is the reproduction coefficient for residues in (kg humus C Mg^{-1}), A_r is the excretions from livestock husbandry (Mg $year^{-1}$) and X_w is the amount of sewage sludge in (Mg $year^{-1}$) applied on agricultural land. "C_{crop}" is the crop specific humus coefficient (kg humus C ha^{-1}) and "S_{crop}" is the crop specific acreage (ha $year^{-1}$).

The crop specific humus coefficient "C_{crop}" is a comprehensive expression which implies the quantity and quality of harvest and root residues as well as the methods of common tillage coupled with the cultivation of the specific crops. The results of the above-mentioned method show how the range of sustainable potential related to cereal straw can vary, maintaining soil fertility, from 26.7% to 44%.

The conclusions drawn from these studies support the need to establish threshold levels for the removal of crop residues for industrial use on site. Differences in soil structure, drainage, slope, duration of waste management, speed of removal of residues, system of processing and cultivation, application of fertilizers and various typologies of climate determine the extent of removal of residues and impact on soil and agronomic productivity for biobased product.

The RothC model is generally reliable and robust even if some weaknesses have been found. The main problems identified in the RothC model were reported in the discussion (sections 4.2 and 4.3). In particular, the two main problems relate to the significant change in SOC according to the different quantity of FYM introduced annually and the erroneous estimate of the total SOC for semi-arid climates.

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7 Annexes

7.1 Annex A

	2014	2015	2016	2017	2018	media
Gennaio	7.2	5.7	5.3	2.5	6.6	5.4
Febbraio	8.9	6.6	8.7	7.1	4.6	7.2
Marzo	11.3	10.0	10.3	11.9	7.7	10.3
Aprile	15.0	13.9	14.6	14.5	15.9	14.8
Maggio	17.7	18.5	17.5	18.2	19.4	18.3
Giugno	22.8	23.0	22.1	24.8	23.2	23.2
Luglio	23.1	27.8	25.9	25.6	25.7	25.6
Agosto	23.6	24.9	24.1	26.2	25.9	24.9
Settembre	19.6	21.2	21.6	19.2	21.6	20.6
Ottobre	17.2	14.5	14.5	15.8	16.5	15.7
Novembre	12.6	10.0	10.2	9.5	11.8	10.8
Dicembre	6.9	5.3	4.4	5.5	4.3	5.3

Table A1: monthly average temperature values [°C] for the years 2014, 2015, 2016, 2017 and 2018 and the average monthly temperature value of 5 years.

anni	2014	2015	2016	2017	2018	media
gennaio	71.4	12.8	30.2	23.0	15.2	30.5
febbraio	65.8	118.8	114.6	40.0	191.6	106.2
marzo	71.4	112.2	66.6	12.4	89.0	70.3
aprile	41.8	68.6	45.0	43.2	11.6	42.0
maggio	32.2	111.8	57.8	49.8	50.0	60.3
giugno	50.6	105.6	85.4	45.4	83.4	74.1
luglio	72.0	0.0	21.4	6.0	23.6	24.6
agosto	96.8	51.8	24.4	31.0	68.6	54.5
settembre	35.0	18.6	83.2	67.2	30.6	46.9
ottobre	62.8	130.2	6.8	21.8	105.0	65.3
novembre	59.0	42.0	86.8	210.0	80.0	95.6
dicembre	94.4	3.0	28.4	35.8	41.6	40.6

Table A2: average monthly precipitation values [mm] for the years 2014, 2015, 2016, 2017, 2018 and the average monthly precipitation value of 5 years.

Time (Month)	BIO pagliabase	DPM pagliabase	HUM pagliabase	RPM pagliabase
11989	0.423872	0.0325041	15.6967	2.79454
11990	0.420735	0.0247943	15.6934	2.76835
11991	0.415841	0.0171075	15.6879	2.73036
11992	0.407737	0.0101301	15.6782	2.67081
11993	0.397219	0.0054489	15.6648	2.59587
11994	0.389434	0.00327212	15.6546	2.54169
11995	0.406028	0.78282	15.673	3.27086
11996	0.433488	0.330734	15.7035	3.08437
11997	0.437757	0.176022	15.7098	2.99395
11998	0.437121	0.113978	15.7102	2.94365
11999	0.430909	0.0620313	15.704	2.86261
12000	0.42633	0.0410636	15.6993	2.81681

Table A3: organic carbon [tC] values of the BIO, HUM, DPM and RPM stocks at the thousandth year from the beginning of the experiment to obtain equilibrium values. Each time corresponds to a time step of one month.

year 10	soc totale
0	31.12
0.1	29.92
0.2	28.72
0.26	27.99
0.3	27.51
0.4	26.31
0.5	25.11
0.6	23.9
0.7	22.7
0.8	21.49
0.9	20.29
1	19.09

Table A4: total SOC [tC] quantity according to the fraction of soil residues at the tenth year. The SOC values were calculated by averaging the tenth year values of the HUM, BIO, DPM and RPM stocks and then the values were added.

year 20	soc totale
0	36.61
0.1	34.86
0.2	33.11
0.26	32.05
0.3	31.35
0.4	29.6
0.5	27.85
0.6	26.1
0.7	24.34
0.8	22.59

0.9	20.84
1	19.09

Table A5: total SOC [tC] quantity as a function of the fraction of soil residues at the twentieth year. SOC values were calculated by averaging the twentieth year values of the HUM, BIO, DPM and RPM stocks and then the values were added.

Fraction of straw	Total SOC
0	30.88
0.1	29.7
0.2	28.52
0.26	27.82
0.3	27.35
0.4	26.17
0.5	24.99
0.6	23.81
0.7	22.64
0.8	21.46
0.9	20.28
1	19.1

Tabella A6: quantity of total SOC [tC] according to the fraction of soil residues at the hundredth year. SOC values were calculated by averaging the hundredth year values of the HUM, BIO, DPM and RPM stocks and then the values were added.

month	jen	Feb	Mar	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dic.
Average high °C	11.5	14	18.1	19.9	24.2	30.5	34.6	34	29	22.1	15.6	11.6
Daily mean °C	6.4	8.3	11.6	13.5	17.6	23.2	26.8	26.3	22	16.1	10.5	7.1
Average low °C	1.3	2.6	5	7.2	11	15.9	18.9	18.6	14.9	10.2	5.3	2.5
Tot Prec (mm/month)	26	25	23	39	44	24	7	9	18	48	39	41
Average relative humidity (%)	76	69	59	58	54	45	39	41	51	66	74	79
Daily Solar incoming radiation(mm/d)	6.14	8.29	11.09	14.13	16.22	17.13	16.74	15.09	12.37	9.32	6.74	5.6
Hargraves formula (mm/d)	1.04401	1.6072	2.59619	3.46746	4.58948	5.90392	6.50823	5.74528	4.0671	2.39779	1.34675	0.9254
Hargraves formula (mm/month)	31.3204	48.216	77.8858	104.024	137.684	177.118	195.247	172.358	122.013	71.9338	40.4026	27.7621

Table A7: dataset input Toledo.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high °C	11.9	13	15.2	17.7	22.8	26.9	30.3	30.6	26.5	21.4	15.9	12.6
Daily mean °C	7.5	8.2	10.2	12.6	17.2	21.1	24.1	24.5	20.8	16.4	11.4	8.4
Average low °C	3.1	3.5	5.2	7.5	11.6	15.3	18	18.3	15.2	11.3	6.9	4.2
Average precipitation mm (inches)	66.9	73.3	57.8	80.5	52.8	34	19.2	36.8	73.3	113.3	115.4	81
Daily Solar incoming radiation(mm/d)	5.62	7.81	10.69	13.9	16.15	17.14	16.72	14.93	12.04	8.87	6.24	5.09
Hargraves formula (mm/d)	0.92794	1.37692	2.08237	2.96901	4.16171	4.99588	5.40537	4.87276	3.43697	2.12096	1.20257	0.85032
Hargraves formula (mm/month)	27.8383	41.3076	62.4712	89.0702	124.851	149.876	162.161	146.183	103.109	63.6289	36.0772	25.5095

Table A8: dataset input Rome.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high °C	6.2	8.8	12.7	16.3	21.7	25.7	28.7	28.7	24.5	18.8	11.6	7.2
Daily mean °C	3.5	5.4	8.85	12.35	17.25	21	23.85	23.85	20	15	8.6	4.5
Average low °C	0.8	2	5	8.4	12.8	16.3	19	19	15.5	11.2	5.6	1.8
Average precipitation mm (inches)	32.8	33.5	46.5	54.8	42.9	48.3	37.8	57.8	69.1	55.7	64.5	40.5
Daily Solar incoming radiation(mm/d)	4.99	7.2	10.19	13.58	16.03	17.14	16.68	14.72	11.62	8.3	5.61	4.45
Hargraves formula (mm/d)	0.54337507	0.95829146	1.65782789	2.53176454	3.68756113	4.48568891	4.76013862	4.20079379	2.8989576	1.65113055	0.7981143	0.50732286
Hargraves formula (mm/month)	16.3012521	28.7487438	49.7348366	75.9529362	110.626834	134.570667	142.804159	126.023814	86.968728	49.5339165	23.9434291	15.2196859

Table A9: dataset input Ravenna.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high °C	8.1	8.4	11.3	14.2	17.9	21	23.5	23.2	19.9	15.5	11.1	8.3
Daily mean °C	5.2	5.3	7.6	9.9	13.3	16.4	18.7	18.5	15.7	12	8	5.5
Average low °C	2.3	2.1	3.9	5.5	8.7	11.7	13.9	13.7	11.4	8.4	4.9	2.7
Average precipitation mm (inches)	55.2	40.9	41.6	43.7	49.4	45.1	44.5	49.5	49.1	68.5	59	55.2
Daily Solar incoming radiation(mm/d)	3.23	5.45	8.66	12.58	15.6	17.05	16.46	13.99	10.31	6.63	3.85	2.72
Hargraves formula (mm/d)	0.39361	0.69519	1.31641	2.26122	3.23744	3.91214	4.09526	3.44357	2.21532	1.15819	0.54413	0.32994
Hargraves formula (mm/month)	11.8083	20.8556	39.4922	67.8366	97.1232	117.364	122.858	103.307	66.4595	34.7458	16.3238	9.89835

Table A10: dataset input London

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high °C	-0.9	0	5.6	14	20.7	23.5	25.6	24.9	19	12.5	4.9	0
Daily mean °C	-3.5	-3	1.8	9.3	15.5	18.5	20.5	19.7	14.2	8.4	1.9	-2.3
Average low °C	-5.8	-5.7	-1.4	5.1	10.8	14.2	16.1	15.2	10.2	4.9	0	-4.6
Average precipitation mm (inches)	36	39	37	46	57	82	71	60	57	41	50	45
Daily Solar incoming radiation(mm/d)	3.49	5.71	8.9	12.74	15.67	17.07	16.5	14.11	10.51	6.88	4.11	2.97
Hargraves formula (mm/d)	0.24304	0.44387	1.01535	2.26598	3.61205	4.15723	4.28516	3.62549	2.19491	1.09325	0.3943	0.21721
Hargraves formula (mm/month)	7.29127	13.3162	30.4606	67.9795	108.361	124.717	128.555	108.765	65.8473	32.7975	11.8291	6.51645

Table A11: dataset input Kiev.

FYM (tC)	FYM (tC)	BIO (tC)	HUM (tC)	DPM (tC)	RPM (tC)
1	1	0.65456541	25.4869449	0.20038281	4.63200306
0.8	0.8	0.60745994	23.5278918	0.18659478	4.27342735
0.6	0.6	0.56034955	21.5683551	0.17280671	3.91481143
0.4	0.4	0.51324598	19.6101204	0.15901878	3.55621469
0.2	0.2	0.46613167	17.6487755	0.1452307	3.19762388
0	0	0.41902478	15.6898143	0.1314426	2.83902633

Table A12: organic carbon (tC) values in the compartments BIO, HUM, DPM and RPM depending on the annual quantity of FYM.

Ocm (tC)	OCm (tC)	BIO (tC)	HUM (tC)	DPM (tC)	RPM (tC)
100	100	23.1722479	868.691283	7.32815172	157.222983
50	50	11.7629197	441.53165	3.73615705	79.9350693
25	25	6.05716226	227.970778	1.93324219	41.28934
10	10	2.63273206	99.8302258	0.84595822	18.1001666
8	8	2.17528116	82.7450657	0.69591396	15.006931
4	4	1.26157246	48.5793356	0.4027445	8.82235028
2	2	0.80410084	31.4922155	0.25270085	5.72907002
1	1	0.5757224	22.9488583	0.17975421	4.18301228
0.8	0.8	0.5298531	21.238529	0.16405806	3.87348035
0.6	0.6	0.4839842	19.5285538	0.14836209	3.56399341
0.4	0.4	0.43812444	17.8211246	0.13266605	3.25446628
0.2	0.2	0.3922593	16.1127254	0.11697001	2.94496295

Table A13: organic carbon (tC) values in the compartments BIO, HUM, DPM and RPM according to the annual quantity of OCm.

Soil Depth (cm)	BIO (tC)	HUM (tC)	DPM (tC)	RPM (tC)
100	0.78806867	30.6365122	0.25343042	5.64331796
90	0.78345127	30.5087286	0.24939865	5.61154286
80	0.77830688	30.3626755	0.24536028	5.57563816
70	0.77352078	30.227151	0.24175482	5.54163714
60	0.77298312	30.2641	0.23954197	5.53738612
50	0.77420555	30.3653551	0.23804233	5.54532653
40	0.774033	30.4082796	0.23648025	5.54262918
30	0.77235178	30.3892429	0.23485279	5.52850857
20	0.7678622	30.2493306	0.23296299	5.49388184
10	0.76195159	30.0514143	0.23071313	5.44829714

Table A14: organic carbon (tC) values in the compartments BIO, HUM, DPM and RPM as a function of the depth of worked soil.

Clay %	BIO (tC)	HUM (tC)	DPM (tC)	RPM (tC)
100	0.83518076	32.7327959	0.23485279	5.52850857
90	0.8357689	32.7404857	0.23545679	5.53543816
80	0.83544667	32.7142408	0.23584592	5.53877102
70	0.83402271	32.6572347	0.23603689	5.54009816
60	0.83054522	32.5285245	0.23603689	5.54009816
50	0.82283831	32.2460939	0.23584592	5.53877102
40	0.80634906	31.6409224	0.23545679	5.53543816
30	0.77235178	30.3892429	0.23485279	5.52850857
20	0.70680122	27.9582551	0.23399124	5.51476041
10	0.59566073	23.8227959	0.23280028	5.49050714
0	0.44290751	18.1311184	0.23121859	5.45825245

Table A15: organic carbon (tC) values in compartments BIO, HUM, DPM and RPM depending on the percentage of clay in the soil.

7.2 Annex B

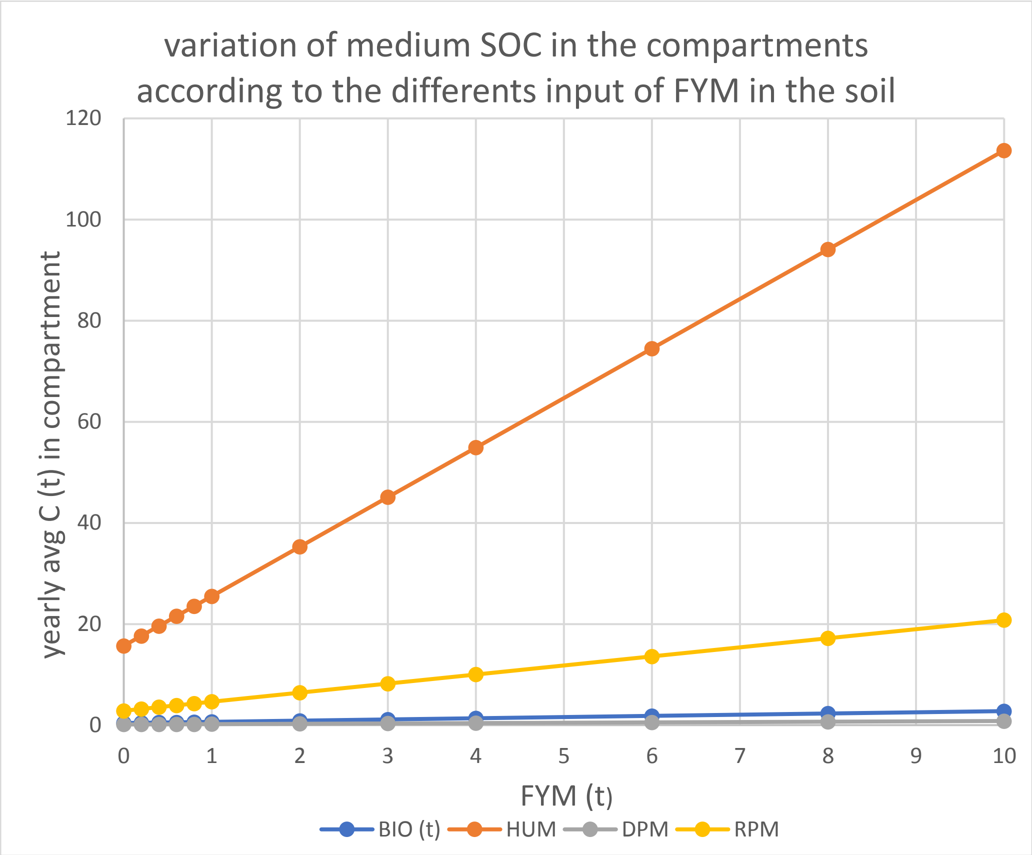

Figure B1: shows the variation of average annual organic carbon in the soil, depending on the different amount of farmyard manure (FYM). Four lines are reported, each of them referred to a specific compartment. In the legeneda, the various lines are specified with a different color.

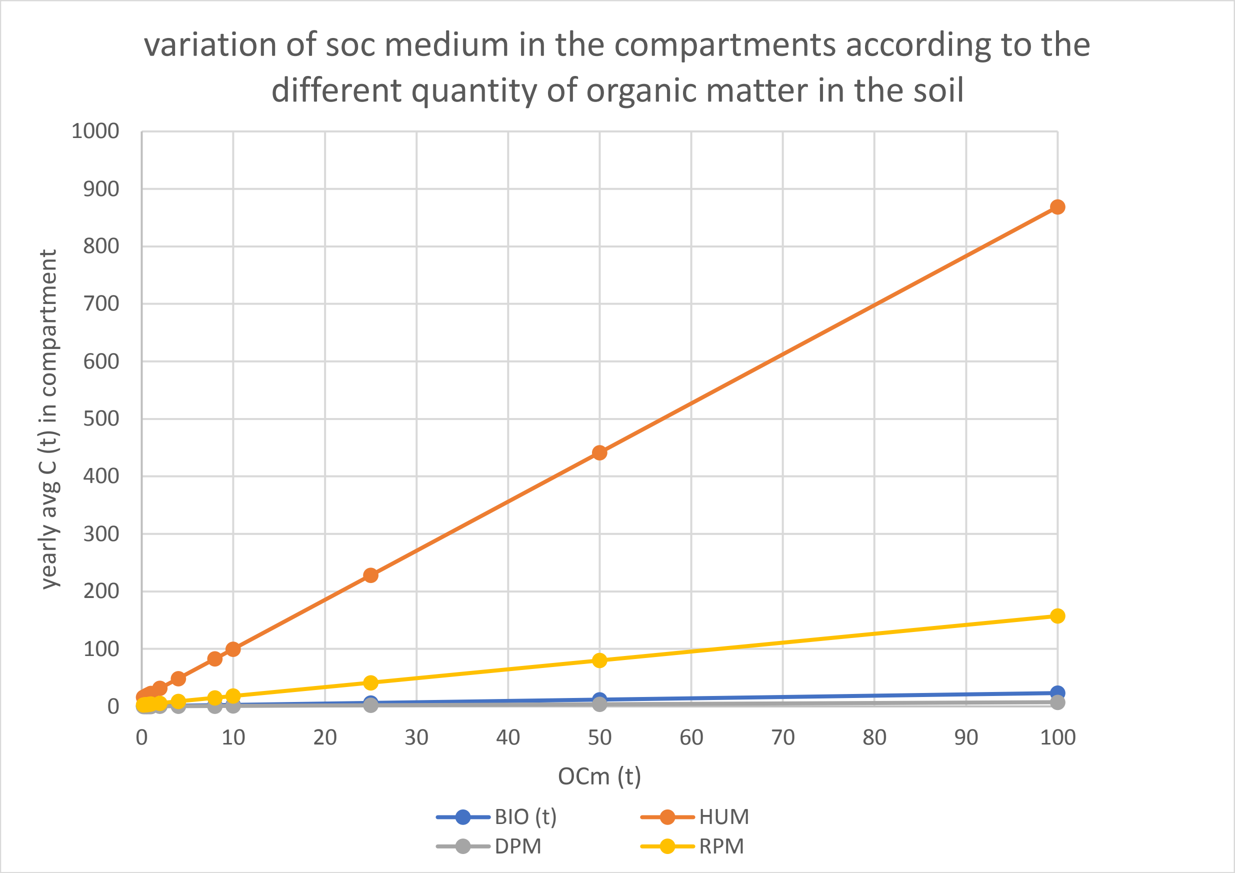

Figure B2: shows the annual average organic carbon variation in the soil for each compartment, depending on the different amount of organic material released into the soil annually. Each line corresponds to a specific compartment.

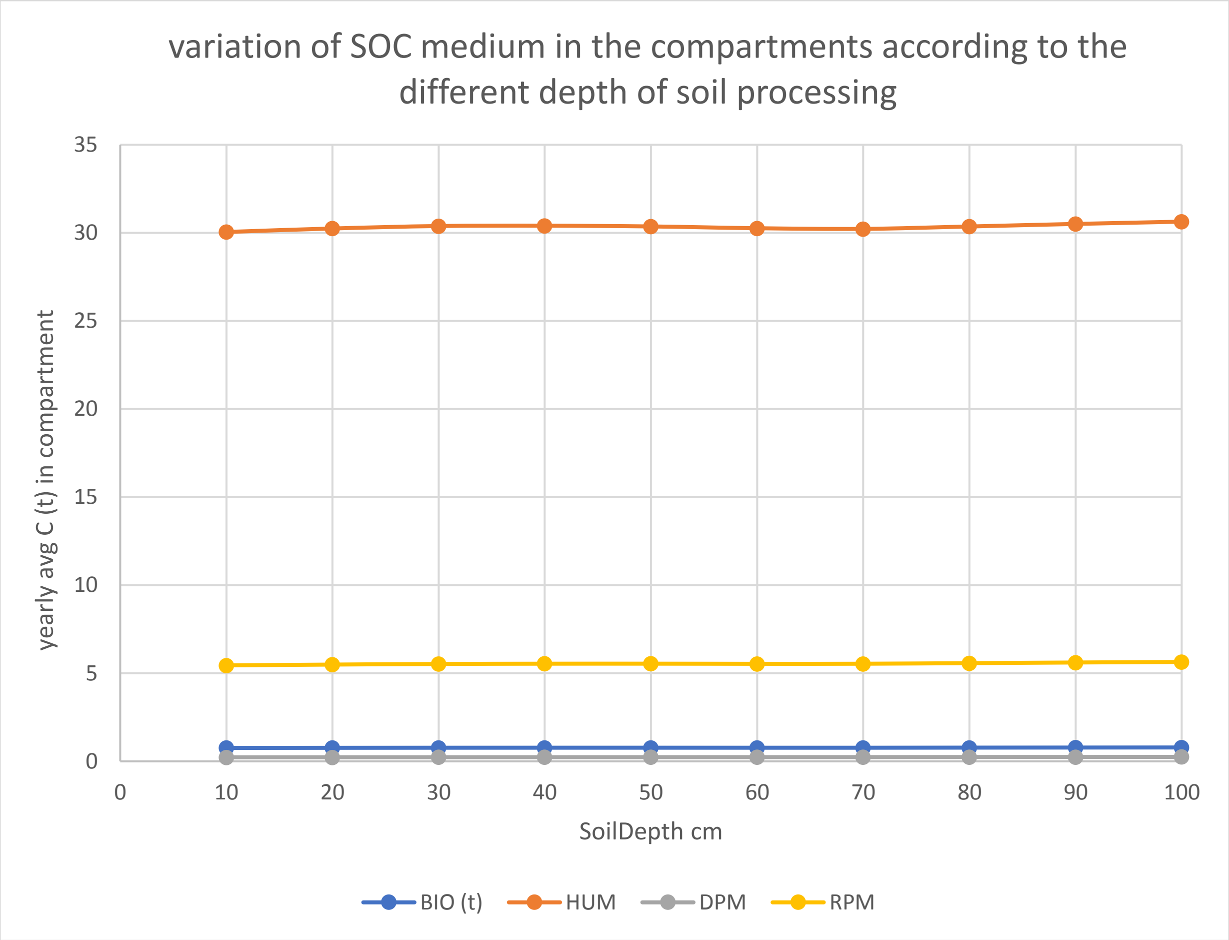

Figure B3: shows the variation of average annual organic carbon in tC in the various compartments according to the different depth of soil processing. Each line corresponds to a specific compartment.

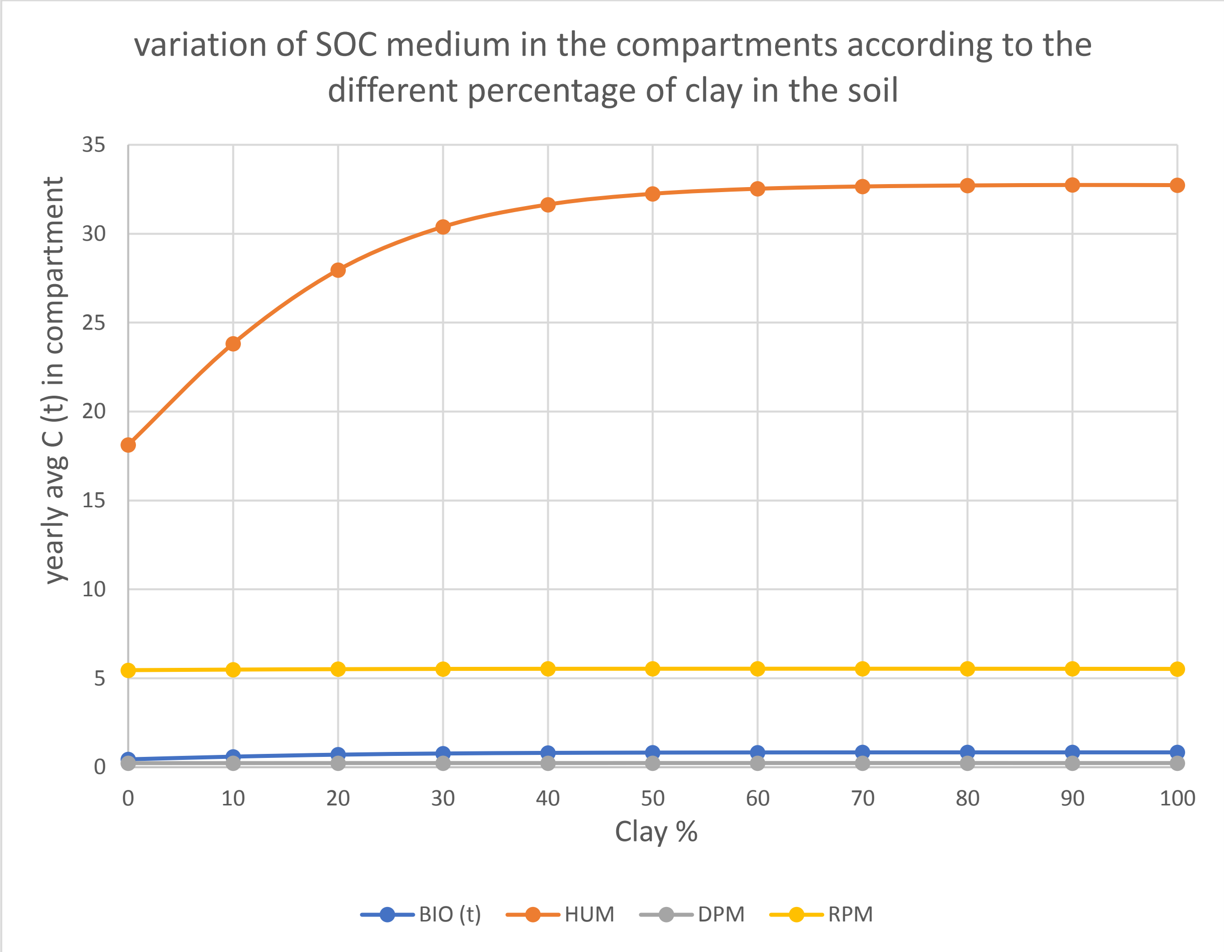

Figure B4: shows the variation of average annual organic carbon in tC in the various compartments according to the different percentage of clay in the soil. Each line corresponds to a specific compartment.