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Factors controlling soil structure dynamics and carbon sequestration across different climatic and lithological conditions

Panakoulia S.K.*[,1], Nikolaidis N.P*., Paranychianakis N.V.*, Menon M.[†], Schiefer J.[§], Lair G.J.[§], Kram P.[¶], Banwart S.A.[r],

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[†] Department of Geography, Winter Street, University of Sheffield, Sheffield S102TN United Kingdom

[r] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom

[§] University of Natural Resources and Life Sciences (BOKU), Vienna, Peter-Jordan-Street 82, 1190 Vienna, Austria

[¶] Czech Geological Survey, Klarov 3, 118 21 Prague 1, Czech Republic

[1] Corresponding author: e-mail address: spanakoulia@gmail.com

Abstract

Soil organic carbon (SOC) is a strong determinant of soil fertility through its positive effects on soil structure and soil chemical and biological properties which in turn stimulate primary production. The objective of this work was to simulate field sites that represent different land uses and management practices in three continents, in order to identify the most important factors controlling soil structure dynamics and C sequestration across different climatic and lithological conditions as well as to quantify the rates of the afore-mentioned processes. The Carbon, Aggregation and Structure Turnover (CAST) model was used to simulate SOC sequestration, aggregate formation, and structure dynamics in three field sites including non tilled soils of natural ecosystems and tilled soils of agricultural fields in Europe (Critical Zone Observatories (CZO) of the SoilTrEC network) and one site in North America. Derived data from the simulations results, of SOC stocks and Water Stable Aggregate (WSA) particle size distribution, together with the respective results of three additional sites (Damma Glacier CZO, Milia (Greece) and Heilongjiang Mollisols (China)) were statistically analyzed in order to determine the factors affecting SOC sequestration and soil structure development. The natural ecosystems include non tilled soils covered with natural local vegetation while the agricultural sites include cultivated and tilled soils covered with crops. The natural ecosystems were represented by Damma Glacier CZO (Switzerland), Heilongjiang Mollisols (China), Koiliaris CZO (Greece), Clear Creek (USA) and the Slavkov Forrest CZO (Czech Republic) whereas the agricultural field sites were located at Heilongjiang Mollisols (China), Koiliaris CZO (Greece), Clear Creek (USA), Marchfeld CZO (Austria) and Milia (Greece). Principal Component Analysis (PCA) identified clay content, bulk density, climatic conditions (precipitation and evapotranspiration), organic matter (OM) and its decomposition rates, as the most important factors that controlled soil structure development. The relative importance of each of these factors differs under differing climatic and lithological conditions and differing stages of soil development. Overall, the modeling results for both natural ecosystems and agricultural fields were consistent with the field data. The model reliably simulated C and soil structure dynamics in various land uses, climatic conditions and soil properties providing support for the underlying conceptual and mathematical modeling and evidence that the CAST model is a reliable tool to interpret soil structure formation processes and to aid the design of sustainable soil management practices.

Keywords: CAST model, soil structure, soil carbon, modeling

1. Introduction

1.1 Soil threats

The adoption of intense agricultural management practices, deforestation and livestock grazing has accelerated soil losses exceeding these of formation by approximately two orders of magnitude (Brantley et al., 2007) with important consequences for the role of soil in vegetation productivity worldwide (CEC, 2006). The EU as part of the 2006 Environment Policy Review previously published the Thematic Strategy for Soil Protection (CEC, 2006) as one of 7 thematic priorities. On 1 January 2016, the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, adopted by world leaders in September 2015, officially came into force. One of the "17 Goals to transform our World" by the United Nations, aims to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (General Assembly, United Nations, 2015). Forests provide shelter to more than 80 per cent of all terrestrial species, 2.6 billion people depend directly on agriculture while 12 million hectares are lost every year due to drought and desertification, where 20 million tons of grain could have been grown. Over 80 per cent of the human diet is provided by plants and 60 per cent of the energy intake is provided only by three cereals. As a result 74 per cent of the poor are directly affected by land degradation (General Assembly, United Nations, 2015). Despite its critical role in the sustenance of the biosphere and meeting the food requirements of more than 7 billion global inhabitants, our knowledge of the soil functions and their response to human activity is far from complete. Thus, a great challenge in the soil science is to improve our understanding of soil processes, particularly for the critical soil functions as they are defined by EU Soil Thematic Strategy, and to develop suitable tools that will allow us to simulate and quantitatively evaluate the impacts of currently applied management practices, the potential impacts of future management practices, or the shifts in environmental conditions including changing land use and climate.

1.2 Soil Organic matter and fertility

Soil fertility strongly depends on soil organic matter (SOM) (Lal, 2015, 2004; Tiessen et al., 1994) by improving soil physical, chemical and biological properties that support primary production by vegetation. The formation of WSA favors the sequestration of C in the soils by protecting it from decomposition (Tisdall and Oades, 1982), reducing in this way CO_2 emissions to the atmosphere (Lal, 2004). The distribution of aggregates between the different size classes has been related to soil structure, SOM and biological activity and represents soil's ability to resist disintegration by disruptive forces (Six et al., 2000). The formation of WSA due to OM addition, improves soil structure and the hydraulic properties of bulk soil through the formation of larger connected pores resulting in increased bulk permeability to fluid flow and improved drainage, while increasing the water holding capacity within the microscopic pores of the larger aggregates. WSA formation is directly related to protection of SOM. SOM can chemically bind to soil mineral particles, making SOM less bioavailable in sorbed form, and also altering the surface properties of soil mineral to favour particle-particle binding and aggregation (Nikolaidis and Bidoglio, 2013). Formation of larger aggregates also provides a redox barrier by holding water within the microscopic pores of the aggregates, which creates a diffusion barrier to O2 and protects the SOM against oxidative microbial degradation. On the other hand, soil structure is affected adversely by the mechanical shearing created by tillage, by freezing and thawing that results from extreme temperature fluctuations, and by the compaction that is due to the use of heavy machinery (Ross et al., 2015).

Restoration of soil fertility through soil management can be achieved by applying appropriate agro-ecological practices (Lal, 2013). Crop rotation, organic-C addition as SOM with associated nutrient elements, reduced tillage, use of cover crops during fallow periods, and controlled grazing are among the most commonly applied practices for sustainable agriculture (Milne et al., 2015). Incorporation of plant residues and organic amendments, such as compost and manure, combined with reduced tilling, enhance C sequestration (Lal, 2015) and plant production (Li et al., 2016; Liao et al., 2015) as well as soil hydraulic properties (hydraulic conductivity, water holding capacity, aeration, and porosity) (Udom et al., 2016). Field experiments with organic amendments have shown that manure improves soil structure and protection of aggregate-associated SOM much more than plant compost in terms of aggregate size and C content (Udom et al., 2016) while evidence has been provided that a mixture of compost (e.g. municipal solid waste derived) and manure (of a rate 70/30 respectively) is equally beneficial, resulting in the increase of the large (>250 μm) WSA mass fraction (Kotronakis et al., 2016; Udom et al., 2016). The effectiveness of these practices depends strongly on OM application rate and composition, climate, and other management practices.

1.3 Modeling soil carbon and structure dynamics

Mathematical models have been developed to simulate and predict soil structure development and C sequestration. These soil properties, as measured by WSA and soil C stocks and their rates of formation, provide proxy measures for soil fertility, defined here as the capacity of soil to support the rate of primary production by vegetation (e.g. g C fixed y^{-1} kg soil $^{-1}$). Over the past decades, several mathematical models were developed to simulate SOC dynamics. Mathematical models such as

CENTURY (Parton et al., 1987), Roth-C (Coleman, K., Jenkinson, 1999; Jenkinson, 1990), DNDC (Gilhespy et al., 2014; Li et al., 2005) and APSIM (Keating et al., 2003), have been used (Álvaro-Fuentes and Paustian, 2010; Andrianaki et al., 2016; Carvalho Leite et al., 2004; Dou et al., 2014; Galdos et al., 2009; GAO et al., 2008; Goglio et al., 2014; Luo et al., 2013; Poeplau and Don, 2015; Stamati et al., 2013b; Zhang et al., 2016) to assess the impact of land management on SOM stocks and to investigate the ability of these models to simulate long term (decades – centuries) SOM dynamics across different ecosystems (Smith et al., 1997). However, these models do not consider the effect of structure and its feedbacks on organic-C dynamics. Several studies have revealed a strong effect of structure on SOC turnover (Jastrow et al., 2007), identifying the link between OM decomposition and aggregate stability (Abiven et al., 2009), and summarizing the dynamics of SOC turnover with changes in soil structure (Nikolaidis and Bidoglio, 2013),. Existing models have been updated (Coleman and Jenkinson, 1999) or further modified (Jenkinson and Coleman, 2008; Nadeu et al., 2015), to incorporate the contribution of factors affecting SOC dynamics and aggregate formation. Over the last decade new models have been developed, and new conceptual frameworks on modeling of soil functions have been proposed. Abiven et al. (2008) developed the Pouloud model to predict the impact of organic residues incorporation on aggregate stability, under field conditions. The Struc-C model (Malamoud et al. 2009) was based on the RothC-26.3 model and linked SOM dynamics with soil aggregation and soil structure. The InVEST model (Nelson et al., 2009) was structured to predict changes in ecosystem services under different land use/land cover change scenarios, incorporating sub-routines assessing water service, soil conservation, C sequestration, biodiversity conservation and commodity production value. The SoilGen2 model (Finke, 2012), which is a further development of the SoilGen1 model (Finke and Hutson, 2008), is a 1D model that simulates the pedogenesis of various parent materials and includes clay formation, and has been used to successfully simulate soil formation. Segoli et al., (2013) developed the AggModel which is a combination of an aggregate dynamics model and a SOM dynamics model, where the C pools are not conceptual but directly measured. Finally, (Stamati et al., 2013a) developed the CAST model using an aggregation mechanism similar to the Struc-C model approach and modeling the carbon sequestration and turnover rates in each aggregate size.

The objective of this work is to use the results of the CAST model simulations of SOC and WSA dynamics for 7 sites around the world with different land use management practices, including natural and agricultural ecosystems, in order to characterize the process rates and the factors controlling soil structure dynamics and C sequestration across different climatic and lithological conditions. A meta-modeling Principal Component Analysis (PCA) integrates the results, clusters the sites by dominant factors influencing SOC and structure dynamics, and identifies the principal factors controlling C sequestration within the clustered sites.

2. Methodology and methods

The CAST model (Stamati et al., 2013a) was used to simulate soil structure dynamics and C sequestration in seven sites across the world. The sites were the Koiliaris CZO, Slavkov Forest CZO, Marchfeld CZO, Clear Creek (Iowa, USA), Damma Glacier CZO, Heilongjiang Mollisols (China) and Milia (Greece), representing various climates, land management practices, soil properties and histories. Table 1 presents the list of the natural ecosystems and agricultural fields of each study site.

[Insert Table 1 here]

The simulations of the CAST model from the Marchfeld CZO, Slavkov Forest CZO, and the agricultural fields of Koiliaris CZO and Clear Creek are presented, while the simulations of Damma Glacier CZO, Heilongjiang Mollisols, Milia and the natural ecosystems of Koiliaris CZO and Clear Creek are described previously (Andrianaki, 2016; Li et al., 2016; Stamati et al., 2013a; Vavlas et al., 2014). The geographic distribution of the sites evaluated in this work is shown in Figure 1.

[Insert Figure 1 here]

All model simulations were performed using consistent guidelines. The simulations were compared in terms of the stocks and flows of C taking into account C sequestration, microbial biomass and the CO_2 flux as well as the changes in the mass distribution of WSA size classes. A comparison of the sites was conducted regarding the rate constants related to the processes of plant biomass fragmentation, formation of micro- and macro-aggregates, SOC decomposition and aggregate disruption. Finally, principal component analysis (PCA) was performed in order to identify the most significant model input, output and calibration parameters as the factors controlling SOC and soil structure dynamics and to identify sites across climatic and lithological gradients with similar responses to SOC sequestration. The model parameters that were included in the PCA analysis were selected based on a parameter sensitivity analysis conducted during the calibration process. The most sensitive (i.e. affecting the simulation results) input, output and model parameters were included in the PCA analysis. The PCA was performed using the MiniTab 17 statistical software.

Methods

2.1 Model Description

The CAST model simulates the mechanisms of aggregation assuming three size classes of aggregates: the silt-clay sized aggregates (AC1, < 53 μm), the micro-aggregates (AC2; 53-250 μm) and the macro-aggregates (AC3, > 250 μm). Figure 2 presents a schematic representation of the concept of WSA formation modified from Stamati et al. (2013). The model assumes that macro-aggregates are formed around large particulate organic matter (POM), followed by the inclusion of micro-aggregates within the macro-aggregates. Microbial decomposers of plant residues provide the extracellular polymeric "glue" by which mineral particles and small aggregates bind to form macro-aggregates around the POM (Phase I). Clay-sized mineral particles with relatively larger specific surface area provide complexation capacity to chemically bind constituent molecular components of SOM to the mineral surfaces, which protects the organic matter and favours inclusion of the clay-size fraction in micro- and macro-aggregate formation (Nikolaidis and Bidoglio, 2013). The macro-aggregate POM is further decomposed and the resulting finely fragmented POM is encrusted with silt-clay sized aggregates leading to the formation of micro-aggregates within macro-aggregates (AC2 in AC3) (Phase II). Decreased microbial activity inside the macro-aggregates due to decreased availability of C and energy following biodegradation of POM reduces the supply of microbial polymers and aggregate disruption occurs (Phase III) with instant release of stable AC2 and AC1 aggregates and the fragmented POM becomes unprotected (Phase IV). When fresh plant residues enter the soil, new macro-aggregates form and the cycle of aggregation and dis-aggregation continues.

[Insert Figure 2 here]

Figure 3 presents a schematic representation of the aggregation process of the CAST model, its aggregate fractions and the C pools sequestered in them. Each arrow represents a mass transformation rate that is translated mathematically by the law of mass action into a linear rate equation with a first-order rate constant that defines the rate as proportional to the mass of the reactive material that is being transformed. The figure shows the phases of WSA formation together with the C pools and fluxes. Fresh plant residue is characterized by the decomposable (DPM) and resistant plant material (RPM). Both DPM and RPM are fragmented and comprise the coarse fraction of DPMc and RPMc which further break down to fine fractions DPMf and RPMf. In the initial phase of aggregation, the AC3 aggregates are comprised of POM, AC1 aggregates, sand, bacteria and fungi. At the second stage, coarse plant material, DPMc and RPMc is decomposed within the AC3 into fine, fragmented DPMf and RPMf which further facilitates the formation of the AC2 micro-aggregates within the AC3. Further biodegradation of the OM decreases the microbial activity and the stability of the macro-aggregates which eventually break down into aggregates of the AC1 and AC2 size fractions.

[Insert Figure 3 here]

The CAST model has been further modified to incorporate the effect of tilling and the impact of frozen soil on the aggregation/disaggregation mechanisms in order to improve the model versatility and extend the conditions that can be represented by simulation of the dynamics of SOM. Tilling was incorporated in the model by making the WSA destruction parameters time-variable. When there is tilling, the destruction rate parameter can be changed to a higher value, depending on the tilling intensity, which upon cessation of tilling subsequently reverts to its initial value. Similarly, frozen soil was incorporated into the model by allowing the rate constants of aggregation and decomposition of OM to vary with temperature. When the ground was defined as frozen, the rate constants of aggregation and OM decomposition can be changed to lower values which, over time, can then revert to their normal values.

The most important input parameters of the CAST model include climatic data such as temperature, precipitation and evapotranspiration (ET), soil properties (silt and clay content and bulk density) and WSA distribution and SOC stock distribution within each of the defined fractions of WSA. More specifically, samples from the topsoil (0-10 cm) for each field site were analyzed for the AC1, AC2 and AC3 fractions of WSA according to the methodology developed by Elliott (1986). AC3 aggregates were further separated to coarse POM (POMc), sand, easily dispersed silt-clay fraction and AC2 aggregates according to Lichter et al. (2008). The AC2 aggregates within the AC3 aggregates were further separated into fine POM (POMf), sand and the silt-clay fractions. The free AC2 aggregates were also separated into POMf and silt-clay fractions. These measurements are performed for every soil sample in order to obtain parameter values both for the initialization and calibration of the model.

2.2 Site Description

The data and experimental results used in the simulations represent conditions of natural ecosystems and agricultural practices. Table 2 presents a summary of the sites and their respective management. A description of the site details follows:

Damma Glacier CZO – Switzerland

Damma Glacier CZO is located at the central Alps, Canton Uri, Switzerland and is a 9.9 km^2 catchment with an elevation range between 1940 and 3630 m above sea level. The glacier has been retreating since 1850, forming a soil chronosequence on a relatively flat area of about 1 km length at an altitude between 1950 and 2050 m. The glacier recession was reversed two times, during 1920 to 1928 and 1970 to 1992, which resulted in two small terminal moraines. Therefore, the chronosequence consists of three groups of soil ages. The youngest sites include soils from 6 to 14 years old, the intermediate group comprises of soils developed between 1930 and 1950 and the oldest group includes soils that started to evolve during 1870 to 1897. The soils have been classified as

Lithic leptosols. The soils at locations in the chronosequence, between those representing these stages of soil formation, have been eroded during glacial advances (Banwart et al., 2011; Bernasconi et al., 2011). The CAST model was used to simulate the accumulation of SOC and the development of soil structure along the chronosequence (Andrianaki et al., 2016). As the chronosequence is not continuous there were 5 simulations, 3 of the different soil ages (young soils, intermediate soils and old soils) and 2 of the readmissions of the glacier. The calibration of the models is based on the extensive dataset available for the Damma Glacier CZO and a climate reconstruction back to 1867 (Smittenberg et al., 2012).

Heilongjiang Mollisols – China

The Heilongjiang Mollisols experimental field site is located in the central region of the Mollisols in Northeast China. The experimental site was established in 2004 at the State Key Experimental Station of Agroecology, Chinese Academy of Sciences, Hailun, Heilongjiang province. The region has a typical temperate continental monsoon climate with a hot summer and cold winter. The soils have evolved from sedimentary materials of loamy loess. Parent material was removed from the C horizon (> 2 m) and replaced the surface soil down to 0.8 m. The experiment was set up to study soil development and restoration from an extremely degraded soil (Li et al., 2016). The field experiment included six treatments, two natural ecosystems and four agricultural fields, in order to compare: a) no-tilled soils under fallow and soil planted with alfalfa and b) tilled soils with rotation of soya and maize in alternate years and different combinations of mineral fertilization (F) and organic (C) amendments. More specifically the tilled soils were managed i) without fertilization and organic amendment (F0C0) after the above-ground biomass was removed, ii) with fertilization and no organic C amendment (F1C0), iii) with fertilization and low amount of organic C input (F1C1) after only partial above-ground biomass of two crops was incorporated into soil, and iv) with fertilization and high amount of organic C input (F1C2) after all the above-ground biomass of the seasonal crop was incorporated into the soil (Li et al., 2016).

Koiliaris CZO – Greece

Koiliaris River catchment is a CZO that represents severely degraded soils due to intense agricultural practices applied for many centuries. It represents typical Mediterranean dry-lands soils evolving under imminent threat of desertification. The Koiliaris CZO is located 25 km east of the city of Chania, Crete, Greece. The total watershed area is approximately 130 km^2 and the main supply of water originates from the White Mountains. An additional area of 50 km^2 outside of the Koiliaris CZO is hydro-geologically connected due to limestone bedrock-karst terrain. Water erosion is recognized as the most important soil degrading threat due to the clearing of forests and natural vegetation, the livestock overgrazing and the tilling of crops (Stamati et al., 2013a, 2013b). Simulations performed for the Koiliaris CZO included both natural ecosystem and agricultural management scenarios and the soil type is calcaric regosol.

Clear Creek – Iowa, USA

The Clear Creek site is located on the outskirts of Iowa City, USA. It is representative of humid continental climates with coarse textured (sandy loam) Mollisols. The cropping period lasts from May to September, while during the winter period the soils are covered by snow. The site has been selected to study the impacts of land use conversion, from agricultural use to natural vegetation, on soil functions (Stamati et al., 2013a, 2013b).

Slavkov Forest CZO – Czech Republic

Slavkov Forest CZO is a Protected Landscape Area located in the northwestern Czech Republic, 120 km west of Prague. The catchment area is 0.273 km^2, with elevations in the range of 829 to 949 m above sea level. There is intense silvilculture with rapidly aggrading Norway spruce monoculture stands since 1850 on nutrient-depleted soils, mostly Podzols developed on granite. The mean stand age is about 40 years, and closed canopy forest covers 82% of the CZO, while clearings with young seedlings cover 18% of the catchment. The most important threats to the soil include nutrient leaching, acidity, metal toxicity, harvest erosion and compaction, low biodiversity due to monoculture, C loss due to elevated organic C export and atmospheric deposition of anthropogenic pollutants (Banwart et al., 2011).

Marchfeld CZO – Austria

The study area is located in the Danube River flood plain downstream of Vienna in the "Marchfeld", with little variation in topography and climate. During alpine glaciations, the Danube continuously incised into the uplifting Tertiary basin fill and accumulated melt water terraces. The floodplain is morphologically subdivided into two units: the recent floodplain sensu stricto and a slightly elevated area covered by older fluvial deposits. The soils in the Marchfeld CZO are Chernozems and create a chronosequence of soil development covering thousands of years, which allows the study of temporal soil development and also the effects of various land uses. The data from Marchfeld CZO were used to perform three simulations of the land use conversion (Rampazzo Todorovic et al., 2014). The initial conditions for each case are freshly deposited sediments with specified soil texture but without structure. Every simulation represents the evolution of C sequestration and soil structure development. The first 200 years of each simulation represent the forest development. The term "*Forest"* refers to the simulation of subsequent steady-state climax forest for 400 years. The term *"Cropland"* refers to the simulation of land use conversion from forest (initial 200 years) to cropland (total 400 years), and the term "*Grassland"* refers to the simulation of land use conversion from forest (initial 200 years) to grassland (total 400 years). The lengths of these periods were inferred from land use history.

Milia – Greece

Milia represents a strongly eroded Eutric Lithosol soil in which restoration practices including terraces formation and incorporation of organic amendments have been applied. The elevation of the study area is 500 m above sea level. Soil samples were collected from three terraces subjected to cultivation with varying compost application practices. Simulations were performed to represent a 10 year period of farming operations (Vavlas et al., 2014). The frequency of compost application was twice per year, through tilling, corresponding to a total application of 8 t C/ha. For terrace 1 (Milia 1), the compost was applied annually for 10 years, while for terrace 2 (Milia 2) it was applied for 8 years followed by 2-years fallow. Finally, for terrace 3 (Milia 3), the organic amendment was applied once every 3 years.

[Insert Table 2 here]

3. Results and Discussion

The interpretation of soil properties, climatic conditions, and land use and management practices in the study areas reveals great variability. The sites are characterized by variable climatic conditions ranging from 0-4 ^{o}C of mean annual temperature of Damma Glacier CZO to 17.6-18.1 ^{o}C of the Greek sites. Precipitation also varies from 1898 mm/yr of Damma Glacier CZO to 510 mm/yr of the Heilongjiang Mollisols. In addition, the sites cover a wide variety of soil types at different stages of soil development, from lithic leptosol of Damma Glacier to eutric lithosols of Milia, to calcaric regosols of Koiliaris and then to more developed podsols, chernozems and mollisols of Slavkov forest, Marchfeld and China/USA respectively. Organic carbon input to the soils at the natural ecosystem sites was approximately proportional to the temperature gradient as it is shown in the site data comparison of Table 3. The lowest C inputs occurred at the Damma Glacier CZO and the Heilongjiang Mollisols and approached 1 t C/ha/yr as a consequence of the short growing season imposed by the low temperatures. As the annual average temperature increases to 5.3 ^{o}C in Slavkov Forest CZO, the C input also increased to 2.75 t C/ha/yr. For higher temperatures, such as that of Clear Creek with 10.3 ^{o}C and of Koiliaris CZO 18.1 ^{o}C, the amount of C inputs was strongly mediated by the precipitation level and its seasonal distribution. For instance, the C input of Clear Creek was 5.8 t C/ha/yr due to the availability of precipitation during the summer (923 mm/yr) whereas in Koiliaris CZO is 3.8 t C/ha/yr due to semi-arid climate (652 mm/yr). Organic carbon input to soils at the agricultural sites depends on the applied management practices; e.g. tilling intensity, below ground biomass of from crop production, and the amount of above ground biomass incorporated to the soil. At these sites, annual C input varies from 0.205 tC/ha at Marchfeld to 8 tC/ha at Milia.

[Insert Table 3 here horizontally]

A schematic diagram of the study sites placed along a temperature gradient representing different stages of soil evolution is illustrated in Figure 4. The sites are placed according to the annual mean temperature, beginning from the Heilongjiang Mollisols and Damma Glacier CZO, to Slavkov Forest CZO, Marchfeld CZO, Clear Creek ending to Milia and Koiliaris CZO. The initial soil conditions for the model simulations of each site, in terms of clay and macro-aggregate content, and the rates of macro-aggregates formation and decomposition of plant litter are also illustrated in Figure 4. The insert in each site are the C flux balances which include C input, C storage and CO_2 emissions. The ordering of sites according to temperature also coincides with the different stages of soil evolution starting from soil formation due to weathering in Damma Glacier CZO and the parent material of Heilongjiang Mollisols, moving to soils used for forestry at Slavkov Forest CZO and arable land at Marchfeld CZO, ending at the relatively degraded soils of Clear Creek and Koiliaris CZO due to permanent cropping and overgrazing. The C flux balances show soil degradation due to C losses represented by the negative values of C storage. The site of Milia is placed outside the circle of soil formation and soil degradation because it represents soil restoration conditions due to organic carbon addition.

[Insert Figure 4 here]

3.1 Calibration results

The simulations for the Koiliaris CZO, Clear Creek, Marchfeld CZO, and Slavkov Forest CZO sites with regard to the distribution of SOC stocks and WAS, and their interpretation with the field data used for model calibration, are shown in Figure 5a and Figure 5b respectively. The calibration parameters of the CAST model and their description are summarized in Table 4.The descriptions of the parameters indicating soil initial conditions are presented in Table SI 1 (Appendix – Supplementary Information).

[Insert Table 4 here]

[Insert Figure 5a here]

[Insert Figure 5b here]

A comparison of the CO_2 fluxes, C stocks, and microbial biomass is presented in Table 5. The table presents the initial C content of each site that ranges from 0.6-14.8 t C/ha at Damma Glacier CZO to 13.5 t C/ha for the Heilongjiang Mollisols to 55.4 t C/ha for Slavkov Forest, to 18.5 t C/ha for Clear Creek and 34.9 t C/ha for Koiliaris CZO soil, for the natural sites. Regarding the agricultural sites, the initial SOC mass ranges from 13.77 t C/ha for the Heilongjiang Mollisols to 58.55 t C/ha for Koiliaris

CZO soil. Milia had an initial SOC mass of 33.9 t C/ha, Clear Creek 32.38 t C/ha and Marchfeld CZO 27.11 t C/ha. The values of initial SOC mass of Damma Glacier CZO and Heilongjiang Mollisols can be explained by the fact that Damma Glacier CZO is a very new, 150-year-old, soil, while the Heilongjiang Mollisols were C horizon soil brought to the soil surface and placed under cultivation. The high value for Slavkov Forest CZO is due to the fact that it is a forested site relatively undisturbed for the past 70 years, while the low value of Clear Creek is due to intense cultivation of the Iowa, USA soils and the sandy / low clay content nature of the soil that offers limited mineral surface for binding and forming organo-mineral complexes that protect and sequester OM. Finally, the initial SOC mass of Koiliaris CZO is indicative of its relatively high clay content and lower intensity of agricultural practices.

[Insert Table 5 here horizontally]

Regarding the natural ecosystems, the young soils of Damma Glacier CZO and Heilongjiang Mollisols sequester higher amounts of the C input, up to 0.31 (28%) and 0.47 t C/h/yr (40%) respectively, while the older soils of the Clear Creek and Koiliaris CZO sequester significant lower proportions, 5% and 13% respectively even though the annual storage is maintained close to that of the young soils (0.27 t C/ha/yr for Clear Creek and 0.48 t C/ha/yr for Koiliaris CZO). These differences can be explained by climatic conditions, soil structure and land use management. Slavkov Forest CZO presents intermediate values with 26% (0.72 t C/ha/yr) of the C input to sequestered annually. The CO_2 emissions follow the opposite trend to that observed for C storage with the young soils having lower emissions compared to the older soils. As for the cultivated sites, the initial SOC mass (Table 3) ranged from 13.77 t C/ha for the Heilongjiang Mollisols to 58.55 t C/ha for Koiliaris CZO soil. Milia had an initial SOC mass of 33.9 t C/ha, Clear Creek 32.38 t C/ha and Marchfeld CZO 27.11 t C/ha. The values of initial SOC mass of Heilongjiang Mollisols can be explained by the fact that the Heilongjiang Mollisols had a well-developed C horizon when the cultivation started. C input ranged from 0.2 t C/ha at Marchfeld to 8 t C/ha in Milia. The data from the Heilongjiang Mollisols showed that the higher the C input, the more the C storage, CO_2 emissions and bacterial biomass. A similar trend was found for the Milia soils. Comparison of sites with similar C input such as the

Koiliaris CZO and Marchfeld CZO revealed that climate (i.e. temperature, rainfall) and water availability through irrigation played an important role. The warmer site (Koiliaris CZO) showed higher CO_2 emissions and loss of organic C despite the lower bacterial stock. Similar emissions of CO_2 to those observed in the Koiliaris CZO were observed in the Heilongjiang Mollisols which could be attributed to the higher C input.

The poor soil structure of the Heilongjiang Mollisols and the Damma Glacier CZO seems to improve with time. This is evident in the Damma Glacier CZO chronosequence where the macro-aggregate AC3 fraction increases from 15% to 46%. In the Heilongjiang Mollisols the macro-aggregate fraction ranged between 29-35%. Even greater proportions of macro-aggregates were found in the Clear Creek and Slavkov Forest CZO soils that approached 79% and 78% respectively. The corresponding proportion for the Koiliaris CZO scrublands was 47%. Finally, in the forests and grasslands of the Marchfeld CZO the macro-aggregate fraction was 45% and 57% respectively.

Regarding the cultivated sites, the Heilongjiang Mollisols macro-aggregate fraction ranged from 21% to 48% depending on the management practice. Milia macro-aggregate fractions ranged from 45% to 70% with the highest proportions corresponding to the treatment of the annual application of organic matter amendment. Finally, the Koiliaris CZO macro-aggregate fraction was 53%, Clear Creek was 74% and Marchfeld CZO was 23%, again reflecting differences regarding climate, agricultural practices and soil properties. A decrease in the macro-aggregate fractionation was observed in Koiliaris CZO natural ecosystem, which was accompanied by an increase in the micro-aggregate fraction AC2. The site of Marchfeld CZO showed a large (277%) increase in AC3 content the first 200 years of forest development, since the site initially was consisted of sediment depositions, with no aggregates and soil structure.

The values for the calibration parameters of the CAST model for the simulations of natural ecosystems and agricultural sites are summarized in Table SI 2 and Table SI 3 respectively, while a range of these values is presented in Table SI 4 in order to provide an initial database for future modeling activities. Overall, the modeling results of the CAST model for both the natural ecosystems and agricultural management sites were consistent with the field data. The model has been able to describe SOC and soil structure dynamics in a wide variety of natural ecosystem and agricultural sites around the world. A broad comparison between the process rates constants of the agricultural management sites and the natural ecosystems shows that the rates of fragmentation, micro aggregation and disruption are higher for the agricultural sites, while the rates for macro aggregation and decomposition of organic matter are higher for the natural ecosystems.

3.2 Factors controlling soil structure dynamics and carbon sequestration

Our findings confirmed those of earlier studies that the factors regulating the sequestration of C in soils are driven by complex interactions within the soil-plant-water system. A principal component statistical analysis (PCA) was employed to classify the soils studied in the present work in terms of their status considering climatic parameters, basic soil properties, SOC and macro-aggregate content at the initial and final stages of simulation and their annual rates of change, C input rates to soil through litter fall and organic amendments, the decomposition rates of the soil C pools, and the magnitude of disruption of the aggregates including the impact of tilling.

The score and the loading plots of the components of the PCA are presented in Figures 6 and 7 in order to illustrate the clustering of the sites and the significance of each parameter in this clustering. The 35 parameters used in the PCA together with the eigenvalues for the first two principal components are summarized in Table SI 5. The most important parameters that explained the variability in the first component are: the initial macro-aggregate fraction as percentage of total mass, the initial value of the SOC normalized to the mass content of the silt and clay, the temperature, the bulk density and the ET. Similarly, the most important parameters included in the second component are: the percent mass fraction of macro-aggregates, the percent mass fraction of silt-sized aggregates, the decomposition rates of humified and bacterial organic C pools, and the fragmentation rate of resistant plant material by soil fauna. PC1 could explain 32.1% of the variability of the samples, while together with PC2 49.7% of the variability.

Figure 6 presents the clustering of the sites as a result of the PCA. A plot of PC1 versus PC2 of all the sites resulted in the development of four clusters. The first cluster includes the sites of Heilongjiang Mollisols (all management practices) and Damma Glacier CZO (new and intermediate soils) which represents soils at their early stage of evolution. For the Heilongjiang Mollisols, this reflects the introduction of C horizon parent material to the soil surface, hence exhibiting characteristics of a young soil. The second cluster includes all the sites of Marchfeld CZO, Slavkov Forest CZO, Damma Glacier CZO (older soils) and the natural ecosystems of Koiliaris CZO. These sites are either natural or set aside sites or flood plain soils with a high degree of fertility. The third cluster includes the agricultural sites of the Koiliaris CZO and all the Clear Creek studies which represent intensively managed soils. Finally, the fourth cluster includes the site of Milia (all management practices) where intensive C sequestration occurs due to large C additions. As it can be seen from Figure 6, PC1 differentiates the sites starting from the left with soils at an early stage of evolution, moving to the second cluster in the middle with mature soils and moving to the upper right of the graph with the intensively managed soils. PC2 differentiates the sites based on the degree of intensification versus natural ecosystem sites but with C addition. Cluster 4 accounts for the Milia site which diverges from the main trend of clusters 1 through 3 due to extensive C addition. Similarly, the sites within cluster 1 identify a trend from the early diagenesis sites of Damma Glacier CZO to the cultivated C horizon sites of the Heilongjiang Mollisols. It is interesting to note that PC2 differentiates the Chinese Heilongjiang Mollisols based on the amount of C added.

[Insert Figure 6 here]

In terms of soil carbon evolution, the four clusters of Figure 6 represent the sites dominated by carbon fixation (Cluster 1), the sites with stable SOC content (Cluster 2), the sites dominated by SOC mineralization and net loss (Cluster 3) and the sites with large artificial SOC addition (Cluster 4).

Figure 7 presents the Loading Plot of the PCA analysis in order to identify the most important parameters contributing to the differentiation of the clusters. The factors contributing to the differentiation of Cluster 1 includes bacterial biomass as a proxy for microbial decomposer activity, SOC storage, the increase of the fertility factor SOC/(silt + clay) and the increase of the macro-aggregate fraction. Cluster 2 represents older soils which have probably reached a steady state. This cluster is placed in the middle of the diagram where all the factors play a seemingly equal role. Cluster 3 represents degraded soils where the decomposition rates of the C pools is higher, the decomposable plant material outweighs the resistant plant material and the disruption of macro-aggregates is increased. Cluster 4 represents soils restored by beneficial intervention practices where the aggregation rates are higher, the plant material is decomposed by fauna and contributes to aggregation. The trend presented in the PCA analysis in Figure 6 is related to the evolutionary nature of the soils beginning from the young soils and parent material, proceeding to the older soils, forests and arable lands, ending either at soil degradation through continuous cultivation or to restoration through beneficial practices of previously intensively managed soils. In broad terms the evolution of soil structure and increasing intensity of human exploitation of the resulting soil functions correlates with the trajectory shown in Figure 6. This trajectory starts from young soils at the left, to productive soils in the centre, to heavily impacted and very intensively managed soils at the upper right. The dotted arrows show the trend of soil evolution within each CZO. For the Heilongjiang Mollisols, the trend starts at the natural ecosystems ending at the cultivation practices. For the Damma Glacier CZO soils, it begins at the young soils, ending at the older soils. For the Marchfeld CZO soils the trend starts at the grassland, moving to forest, ending at the agricultural land. At Koiliaris CZO and Clear Creek the trend starts at natural ecosystem ending at cultivation. At Milia the trend of soil restoration starts at low C amendment addition ending at higher application. It appears that the first two principal components can account for the variability that describes the evolutionary nature of soil from formation to cultivation as well as a reverse in this trajectory when moving from intensive utilization with soil degradation to restoration.

[Insert Figure 7 here]

Figure 7 presents the variables with the higher values, either positive or negative, of the factors with the higher impact on soil structure dynamics and C sequestration. These variables include soil bulk density, clay content, temperature, ET, initial SOC mass and AC3 fraction, decomposition rates of the

BIO and HUM pools, the contribution of plant litter and silt clay sized aggregates on AC2 and AC3 formation, the formation rate of AC3 aggregates and the fragmentation of resistant plant material through fauna. Briefly the factors controlling soil structure and C dynamics are related to soil properties, climatic conditions, decomposition rates of organic matter, and formation rates and the predominant buildersers of macro aggregates.

4. Conclusions

In this study, the CAST model was modified to incorporate the impact of tilling and frozen soil conditions on aggregate formation and SOC sequestration. The modified CAST model was used to simulate 20 cases of different soil management practices located at 7 sites across a wide range of climatic conditions, land uses, and parent material. The CAST model can successfully simulate and predict aggregate formation and C sequestration on soils across the world, under a variety of climatic, lithological and agricultural conditions. The principal component analysis indicated the predominant factors controlling soils structure and C sequestration to be the plant litter contribution to aggregate formation, the decomposition rates of the humified and bacterial C pools, the initial state of soil in terms of SOC, silt and clay and macro-aggregate contents, the fragmentation rate of plant material through earthworms and other fauna, the macro-aggregate formation rates, the temperature and evapotranspiration and the soil bulk density. The model reliably simulated soil C and soil structure dynamics for a wide variety of land uses, climatic and lithological conditions and soil properties providing support for the underlying conceptual and mathematical model and evidence that the CAST model provides a valuable quantitative analysis tool to interpret soil structure formation processes and to aid the design of sustainable soil management practices which support WSA formation.

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Tables

1. Table 1: Natural ecosystems (non tilled soils) and agricultural fields (tilled soils) of the study sites

2. Natural Ecosystems	**3. Agricultural Fields**
4. Koiliaris CZO – Calcaric Regosols - Set aside field	5. Koiliaris CZO – Calcaric Regosols - Cropland
6. Marchfeld CZO – Chernozems - Forest development 7. Marchfeld CZO – Chernozems - Land use conversion from forest to grassland	8. Marchfeld CZO – Chernozems -Land use conversion from forest to cropland
9. Slavkov Forest CZO – Podsols - Forestry	10.
11. Damma Glacier CZO - Lithic Leptosols	12.
13. Heilongjiang Mollisols: 2 fields with Natural Fallow and Alfalfa	14. Heilongjiang Mollisols: 4 fields with Soybean –Maize rotation
15. Clear Creek – Millisols - Set aside field	16. Clear Creek – Mollisols - Cropland
17.	18. Milia: Eutric Lithosols - 3 fields with different practices of compost application - Tilling

Table 2: Summary of sites simulated with a description of soil management

Site - Treatment	Description
Heilongjiang Mollisols - NatF	Natural fallow – No fertilization, Organic Input, No Tilling
Heilongjiang Mollisols - Alfa	Alfalfa – No fertilization, Organic Input, No Tilling
Heilongjiang Mollisols - F0C0	Soybean-maize rotation -– No fertilization, No Organic Input, Tilling
Heilongjiang Mollisols - F1C0	Soybean-maize rotation -– Fertilization, No Organic Input, Tilling
Heilongjiang Mollisols - F1C1	Soybean-maize rotation -– Fertilization, Low Organic Input, Tilling
Heilongjiang Mollisols - F1C2	Soybean-maize rotation -– Fertilization, High Organic Input, Tilling
Koiliaris Natural	Koiliaris set aside
Koiliaris Agricultural	Koiliaris agricultural management – Green vegetable, Light Tilling
Clear Creek Natural	Clear Creek set aside
Clear Creek Agricultural	Clear Creek agricultural management – Corn and Soybeans, Tilling
Milia1	Milia terrace 1 - compost application for 10 years, every year
Milia2	Milia terrace 2 - compost application for 8 years, every year and then fallow for 2 years
Milia3	Milia terrace 3 - compost application for 10 years, every 3^{d} year
Damma Young	Young soils of Damma Glacier CZO - ages from 6 to 14 years old
Damma Intermediate	Intermediate soils of Damma Glacier CZO - ages from 57 to 79 years old
Damma Old	Old soils of Damma Glacier CZO - ages from 108 to 140 years old
Marchfeld Forest	Marchfeld forest development (0 - 400 years forest)
Marchfeld Grassland	Marchfeld land use conversion from forest to grassland (0 - 200 year forest – 200-400 year grassland)
Marchfeld Agricultural	Marchfeld land use conversion from forest to cropland (0 - 200 year forest – 200-400 year cropland)
Slavkov Forest	Slavkov Forest CZO - Forestry

Table 3: Comparison of the site data: SOC, Soil Characteristics and Meteorological data

	Soil characteristics			*SOC characteristics*		*Meteorological Data*		
Site	*Bulk Density (gr/cm³)*	*Silt clay (%)*	*Clay (%)*	*DPM to RPM ratio*	*Initial SOC mass (t C/ha-yr)*	*Mean Temperature (°C)*	*Mean Precipitation (mm)*	*Mean Pan Evaporation (mm)*
Heilongjiang Mollisols Alfa	1.35	77.6	42.0	0.25	13.77	2.5	510.6	514
Heilongjiang Mollisols NatF	‘’	‘’	‘’	0.15	‘’	‘’	‘’	‘’
Heilongjiang Mollisols F0C0	‘’	‘’	‘’	0.40	‘’	‘’	‘’	‘’
Heilongjiang Mollisols F1C0	‘’	‘’	‘’	1.00	‘’	‘’	‘’	‘’
Heilongjiang Mollisols F1C1	‘’	‘’	‘’	1.20	‘’	‘’	‘’	‘’
Heilongjiang Mollisols F1C2	‘’	‘’	‘’	1.44	‘’	‘’	‘’	‘’
Koiliaris CZO Natural	1.18	67.0	30.0	0.67	34.92	18.1	651.9	1916
Koiliaris CZO Agricultural	1.11	‘’	‘’	1.44	58.55	‘’	‘’	‘’
Milia 1	1.00	34.0	3.30	0.43	33.90	17.6	1494.6	1601.7
Milia 2	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
Milia 3	‘’	‘’	‘’	‘’	‘’	‘’	‘’	‘’
Clear Creek Natural	1.11	37.0	7.00	1.51	18.52	10.3	923.0	1413.6
Clear Creek Agricultural	‘’	‘’	‘’	2.00	32.38	‘’	‘’	‘’
Slavkov Forest CZO	1.30	47.0	11.00	0.25	55.36	5.3	1049.0	442.7
Marchfeld CZO Forest	2.00	73.6	16.36	0.25	20.00	9.1	687,0	727,7

Marchfeld CZO Grassland	1.26	‘’	‘’	0.70	27.11	‘’	‘’	‘’
Marchfeld CZO Cropland	1.26	‘’	‘’	1.44	‘’	‘’	‘’	‘’
Damma Glacier CZO Young Soils	1.50	35.0	3.10	1.44	0.60	4.0	1898.3	242.7
Damma Glacier CZO Intermediate Soils	1.50	‘’	‘’	‘’	1.05	2.9	‘’	‘’
Damma Glacier CZO Old soils	1.00	‘’	‘’	‘’	13.5	2.7	‘’	‘’

‘’ : The same value as the above cell

DPM = decomposable plant material

RPM = resistant plant material

Table 4: Description of the Calibration Parameters of the CAST model

Main CAST model calibration parameters		Description
Fragmentation	RPM to RPMc	Rate constant of fragmentation of Resistant Plant Material to coarse Resistant Plant Material
	RPMc to RPMf	Rate constant of fragmentation of coarse Resistant Plant Material to fine Resistant Plant Material
	RPMc(AC3) to RPMf(AC3)	Rate constant of fragmentation of coarse Resistant Plant Material to fine Resistant Plant Material within macro-aggregates
	DPMc(AC3) to DPMf(AC3)	Rate constant of fragmentation of coarse Decomposable Plant Material to fine Decomposable Plant Material within macro-aggregates
Macroaggregation	RPMc	Rate constant of coarse resistant plant material mass transfer for macro aggregate formation
	DPMc	Rate constant of coarse decomposable plant material mass transfer for macro aggregate formation
Microaggregation	RPMf(AC2inAC3)	Rate constant of fine resistant plant material mass transfer for micro aggregate formation within the macro aggregates
	DPMf(AC2inAC3)	Rate constant of fine decomposable plant material mass transfer for micro aggregate formation within the macro aggregates
Decomposition	fresh plant input(DPM)	Rate constant of decomposition of decomposable plant material from the plant litter pool
	BIO(AC1) within AC3	Rate constant of decomposition of Biomass carbon pools in Aggregate type 1 within Aggregate Type 3 ($AC1_{withinAC3}$)
	HUM(AC1) within AC3	Rate constant of decomposition of Humus in Aggregate type 1 within Aggregate Type 3 ($AC1_{withinAC3}$)
	BIO(AC2) within AC3	Rate constant of decomposition of Biomass carbon pools in Aggregate type 2 within Aggregate Type 3 ($AC2_{withinAC3}$)
	HUM(AC2) within AC3	Rate constant of decomposition of Humus in Aggregate type 2 within Aggregate Type 3 ($AC2_{withinAC3}$)

	BIO(AC2)	Rate constant of decomposition of Biomass carbon pools in Aggregate type 2
	HUM(AC2)	Rate constant of decomposition of Humus in Aggregate type 2
	BIO(AC1)	Rate constant of decomposition of Biomass carbon pools in Aggregate type 1
	HUM(AC1)	Rate constant of decomposition of Humus in Aggregate type 1
Contribution in macroaggregation	RPMc	Percent composition of macro aggregates (AC3) by coarse resistant plant material
	DPMc	Percent composition of macro aggregates (AC3) by coarse decomposable plant material
	AC1	Percent composition of macro aggregates (AC3) by silt clay sized aggregates (AC1)
	AC2	Percent composition of macro aggregates (AC3) by micro aggregates (AC2)
Contribution in microaggregation	RPMfwithin AC3	Percent composition of micro aggregates (AC2) by fine resistant plant material within macro aggregates (AC3)
	DPMfwithinAC3	Percent composition of micro aggregates (AC2) by fine decomposable plant material within macro aggregates (AC3)
	AC1within AC3	Percent composition of micro aggregates (AC2) by silt clay sized aggregates (AC1) within macro aggregates (AC3)
Disruption	DPM_f+DPM_c within AC3	fine and coarse DPM pool contents of the AC3 aggregate type, below which macro-aggregates are considered unstable
	DPM_f+DPM_c AC2 within AC3	fine and coarse DPM pool contents of the AC2 aggregate type within AC3 aggregate type, below which micro aggregates within macro aggregates are considered unstable
	DPM_f+DPM_c within AC2	fine and coarse DPM pool contents of the AC2 aggregate type, below which micro-aggregates are considered unstable

Table 5: Comparison of simulation results with regard to: Annual C stock and fluxes

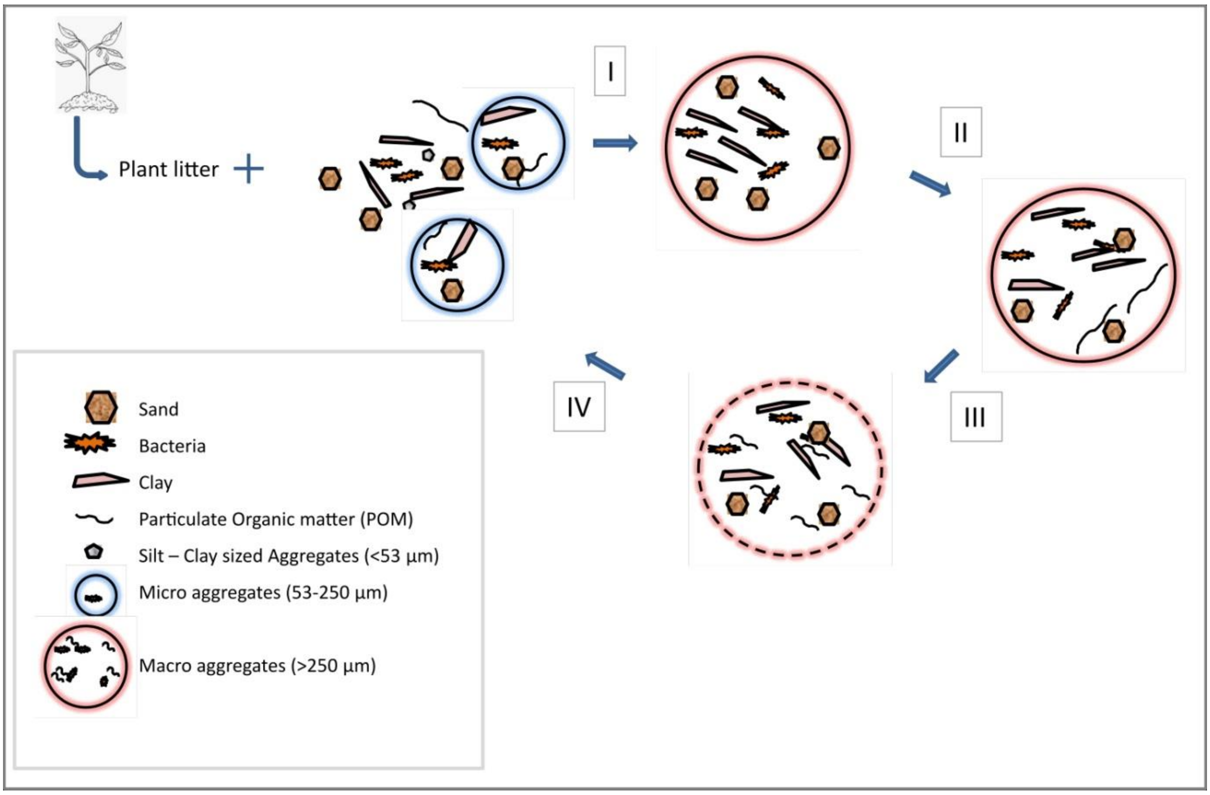
Site	Simulation period (y)	Annual C Input (t C/ha/yr)			Annual C Storage (t C/ha/yr)			Annual CO_2 emissions (t C/ha/yr)			Bacterial Stock (BIO - t C/ha/yr)	
		Average	*min*	*max*	*Average*	*min*	*max*	*Average*	*min*	*max*	*Average*	*% of total stock*
Heilongjiang Mollisols - NatF	10	0.76	0.00	0.95	0.37	-0.61	1.12	0.33	0.08	0.49	8.00	4.49
Heilongjiang Mollisols - Alfa	‘’	0.94	‘’	1.17	0.47	‘’	1.31	0.41	0.11	0.57	8.35	4.52
Heilongjiang Mollisols - F0C0	‘’	0.69	‘’	0.86	0.26	-0.54	0.65	0.38	0.11	0.6	8.51	4.92
Heilongjiang Mollisols - F1C0	‘’	1.05	‘’	1.31	0.32	‘’	0.71	0.67	0.26	1.15	10.17	5.72
Heilongjiang Mollisols - F1C1	‘’	2.27	‘’	2.84	0.84	‘’	1.57	1.36	0.26	2.43	13.6	6.51
Heilongjiang Mollisols - F1C2	‘’	2.96	‘’	3.70	0.99	‘’	2.42	1.89	0.26	3.69	16.18	7.30
Koiliaris CZO Natural	100	3.80	3.80	3.80	0.48	-0.8	1.07	3.29	2.73	4.47	15.8	2.10
Koiliaris CZO Agricultural	40	0.36	0.36	0.36	-0.65	-2.34	-0.31	0.92	0.57	2.58	11.60	2.30
Milia 1	20	8.00	8.00	8.00	2.16	0.28	4.29	5.64	2.61	7.72	39.80	5.54
Milia 2	‘’	3.20	0.00	‘’	-0.21	-5.59	4.29	3.2	1.23	5.59	30.76	5.98
Milia 3	‘’	1.20	0.00	‘’	-0.65	-5.58	5.72	1.65	0.66	3.09	18.64	5.39

Clear Creek Natural	100	5.60	5.60	5.60	0.27	0.03	2.00	5.29	2.79	5.57	36.35	7.50
Clear Creek Agricultural	40	5.44	5.44	5.44	-0.42	-1.15	-0.12	5.35	5.07	6.19	7.90	3.08
Slavkov Forest CZO	20	2.75	2.75	2.75	0.72	-0.97	0.93	1.98	1.81	2.78	24.08	3.22
Marchfeld CZO Initial Forest	200	0.22	0.22	0.22	0.04	0.04	0.04	0.18	0.08	0.29	17.48	6.01
Marchfeld CZO Grassland	‘’	0.15	0.15	0.15	0.07	0.05	0.09	0.08	0.06	0.09	28.16	6.79
Marchfeld CZO Cropland	‘’	0.21	0.21	0.21	-0.04	-1.03	0.01	0.24	0.19	1.23	32.56	13.22
Damma Glacier CZO - Young Soils	14	0.07	0.07	0.07	0.03	0.02	0.03	0.04	0.02	0.04	3.86	36.56
Damma Glacier CZO - Intermediate Soils	44	0.72	0.10	1.80	0.31	0.03	0.82	0.4	0.04	1.11	4.72	12.40
Damma Glacier CZO - Old soils	40	1.12	0.20	2.00	0.24	-0.10	0.60	0.81	0.28	1.45	12.11	14.08

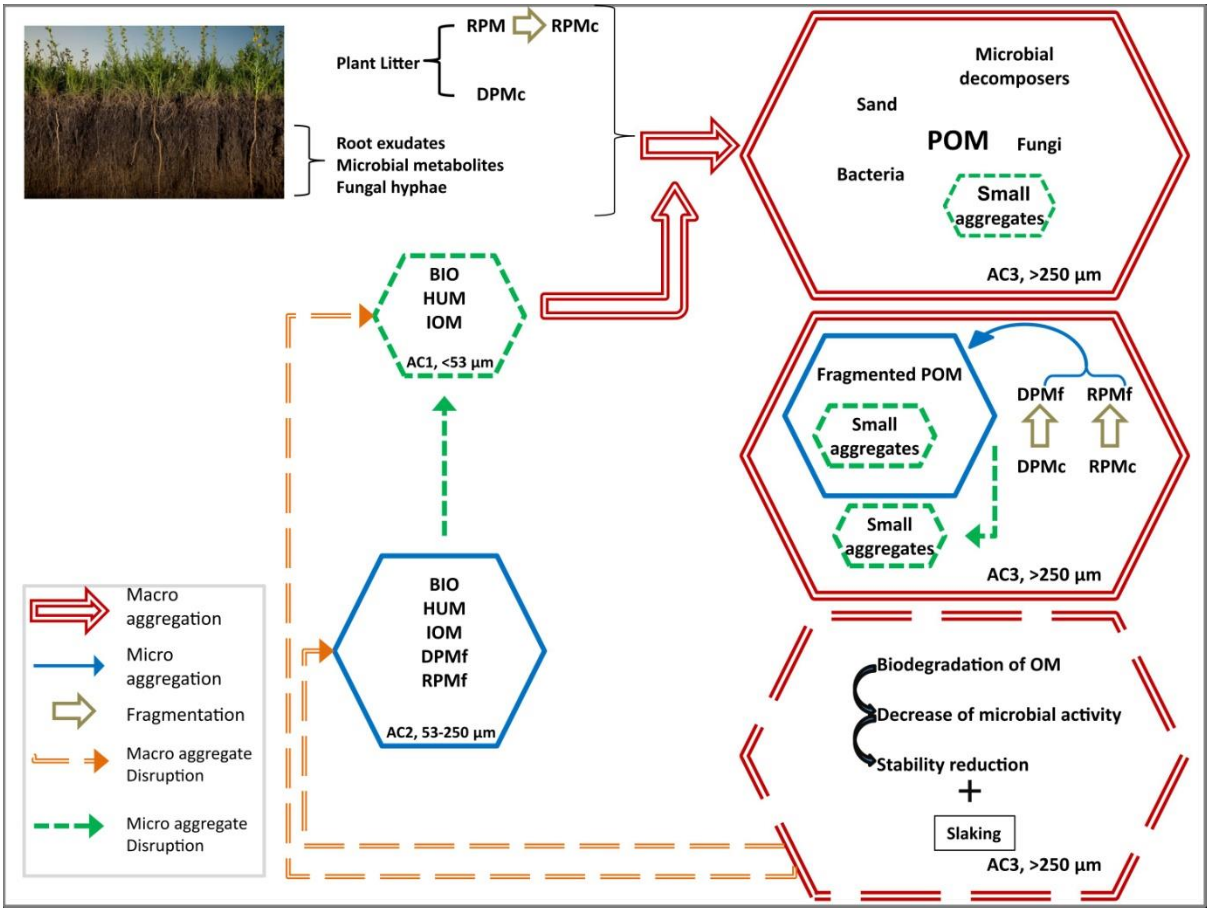
‘’: The same value as the above cell

Figures

Figure 1

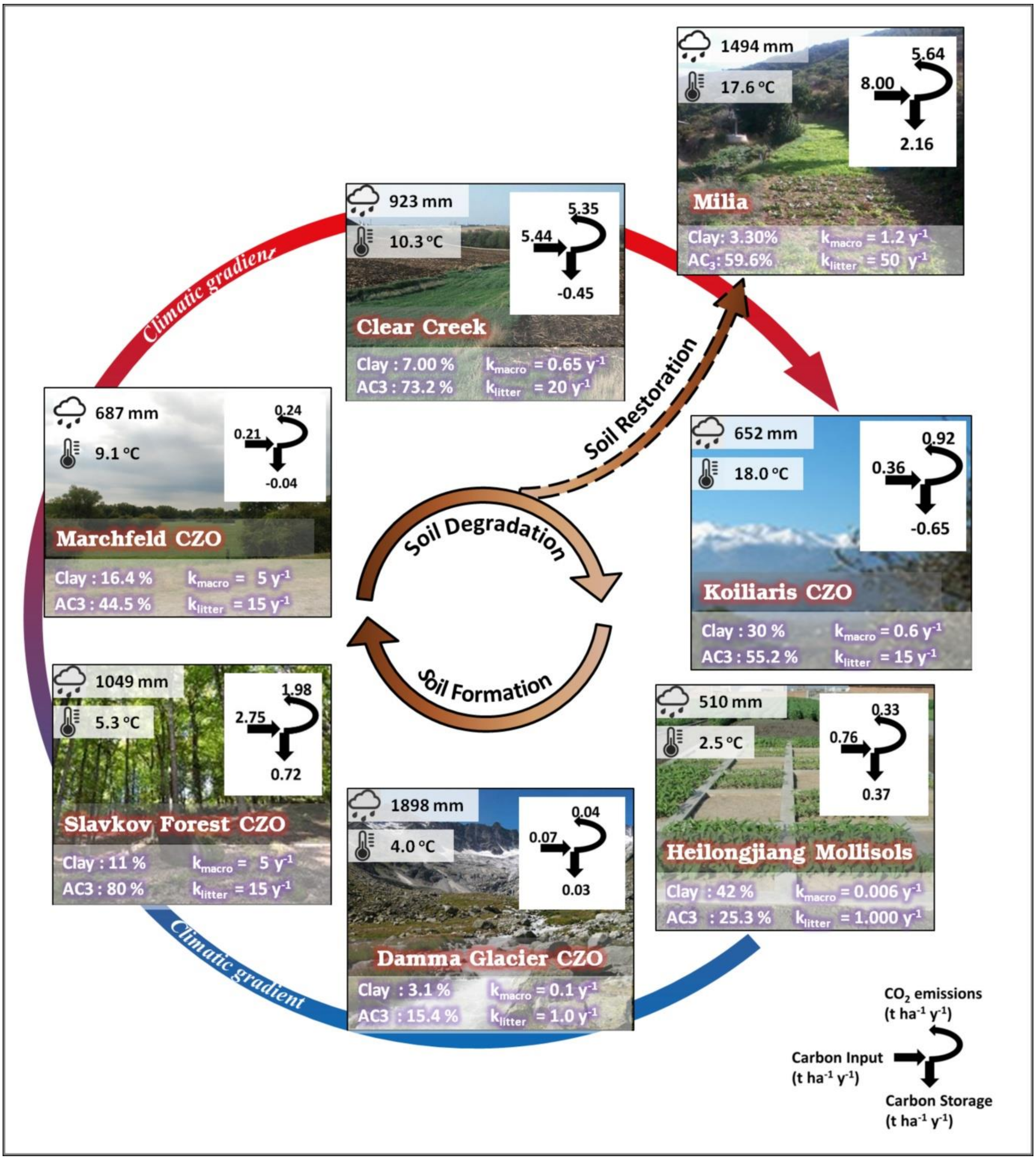


720 Figure 2



721

722 Figure 3



Climatic gradient
923 mm
10.3 °C
5.35
5.44
-0.45
Clear Creek
Clay : 7.00 %
AC3 : 73.2 %
k_macro = 0.65 y-1
k_litter = 20 y-1
1494 mm
17.6 °C
5.64
8.00
2.16
Milia
Clay: 3.30%
AC3: 59.6%
k_macro = 1.2 y-1
k_litter = 50 y-1
687 mm
9.1 °C
0.24
0.21
-0.04
Marchfeld CZO
Clay : 16.4 %
AC3 : 44.5 %
k_macro = 5 y-1
k_litter = 15 y-1
Soil Restoration
Soil Degradation
Soil Formation
652 mm
18.0 °C
0.92
0.36
-0.65
Koiliaris CZO
Clay : 30 %
AC3 : 55.2 %
k_macro = 0.6 y-1
k_litter = 15 y-1
1049 mm
5.3 °C
1.98
2.75
0.72
Slavkov Forest CZO
Clay : 11 %
AC3 : 80 %
k_macro = 5 y-1
k_litter = 15 y-1
510 mm
2.5 °C
0.33
0.76
0.37
Heilongjiang Mollisols
Clay : 42 %
AC3 : 25.3 %
k_macro = 0.006 y-1
k_litter = 1.000 y-1
1898 mm
4.0 °C
0.04
0.07
0.03
Damma Glacier CZO
Clay : 3.1 %
AC3 : 15.4 %
k_macro = 0.1 y-1
k_litter = 1.0 y-1
Climatic gradient
CO2 emissions (t ha-1 y-1)
Carbon Input (t ha-1 y-1)
Carbon Storage (t ha-1 y-1)

Figure 4

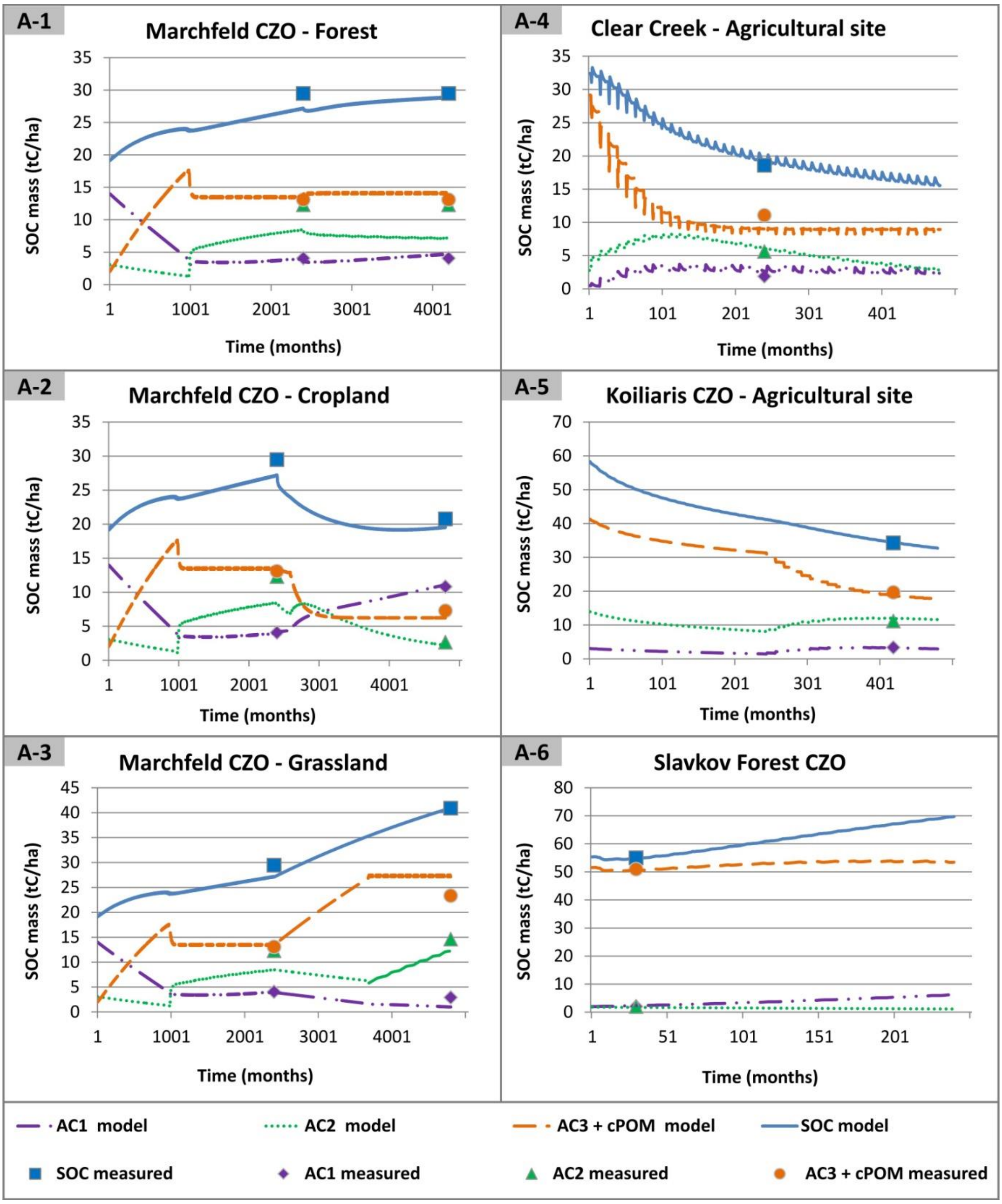
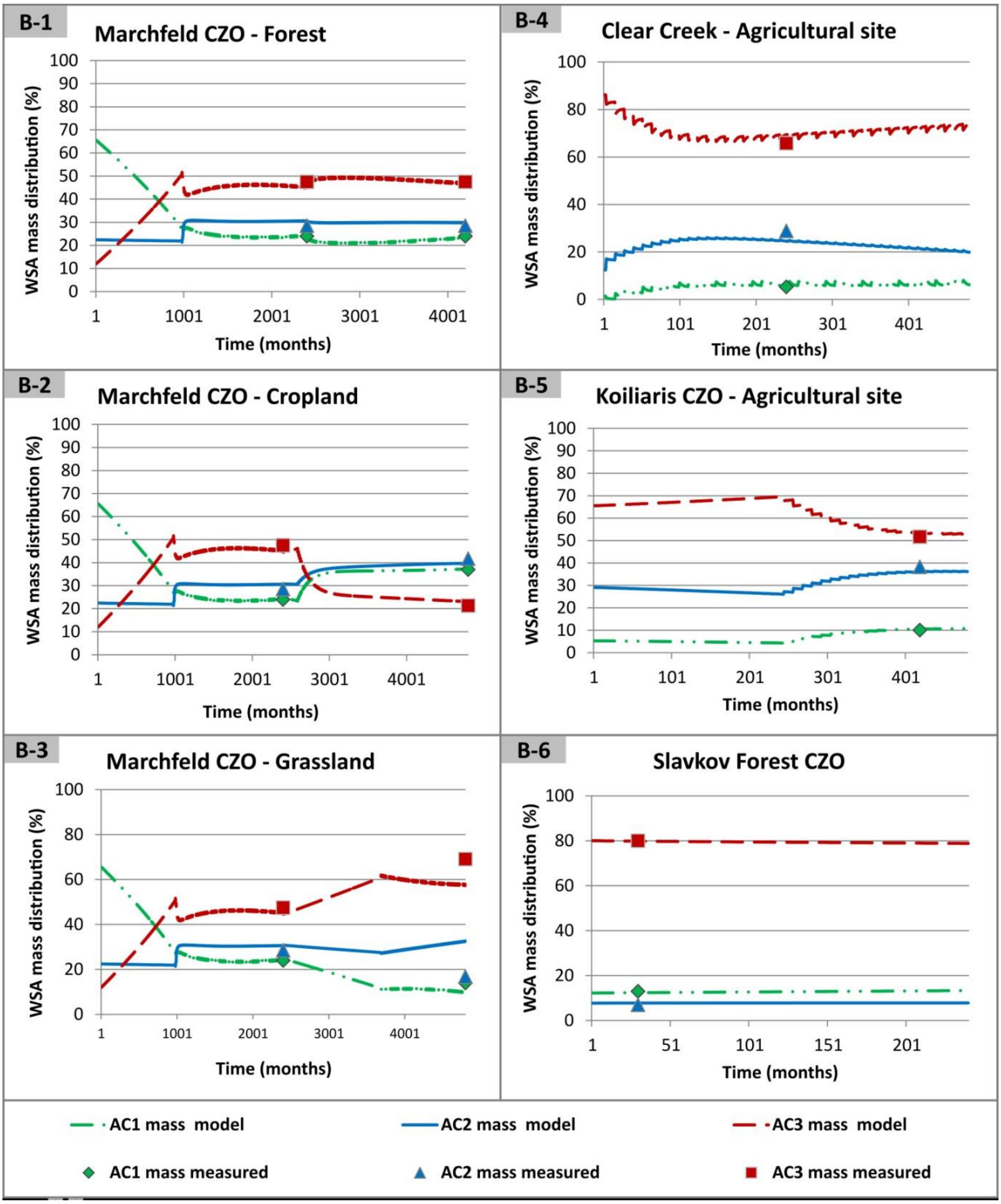

A-1
Marchfeld CZO - Forest
A-2
Marchfeld CZO - Cropland
A-3
Marchfeld CZO - Grassland
A-4
Clear Creek - Agricultural site
A-5
Koiliaris CZO - Agricultural site
A-6
Slavkov Forest CZO
SOC mass (tC/ha)
Time (months)
AC1 model
AC2 model
AC3 + cPOM model
SOC model
SOC measured
AC1 measured
AC2 measured
AC3 + cPOM measured

Figure 5a



B-1
Marchfeld CZO - Forest
B-4
Clear Creek - Agricultural site
B-2
Marchfeld CZO - Cropland
B-5
Koiliaris CZO - Agricultural site
B-3
Marchfeld CZO - Grassland
B-6
Slavkov Forest CZO
WSA mass distribution (%)
Time (months)
AC1 mass model
AC2 mass model
AC3 mass model
AC1 mass measured
AC2 mass measured
AC3 mass measured

Figure 5b

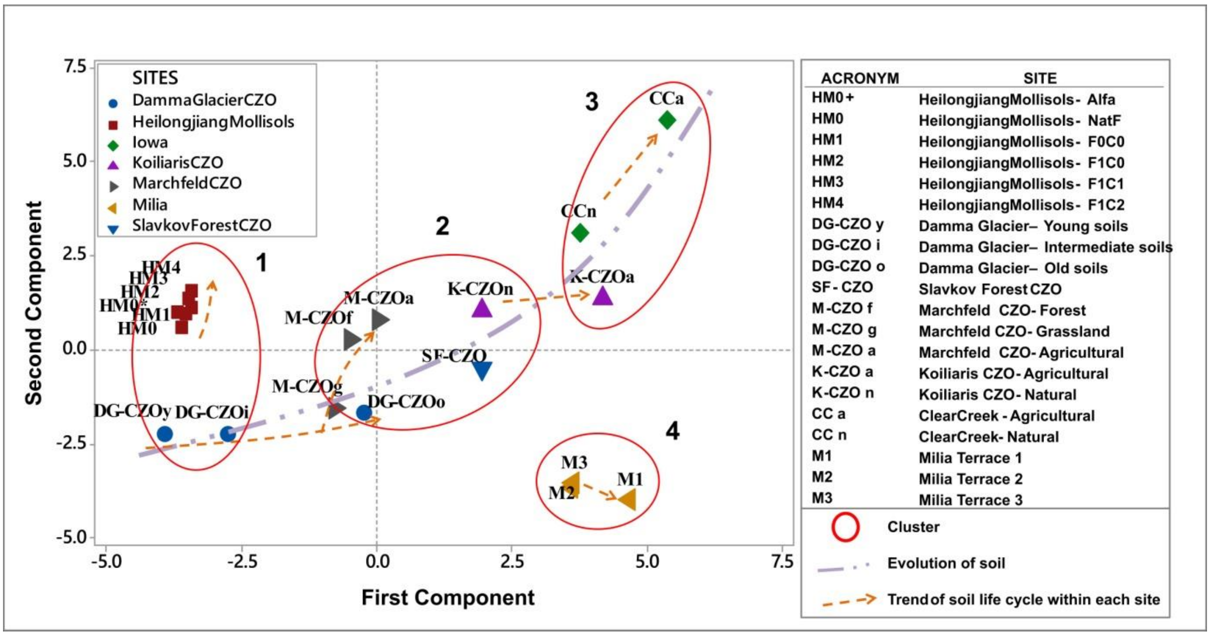


Figure 6

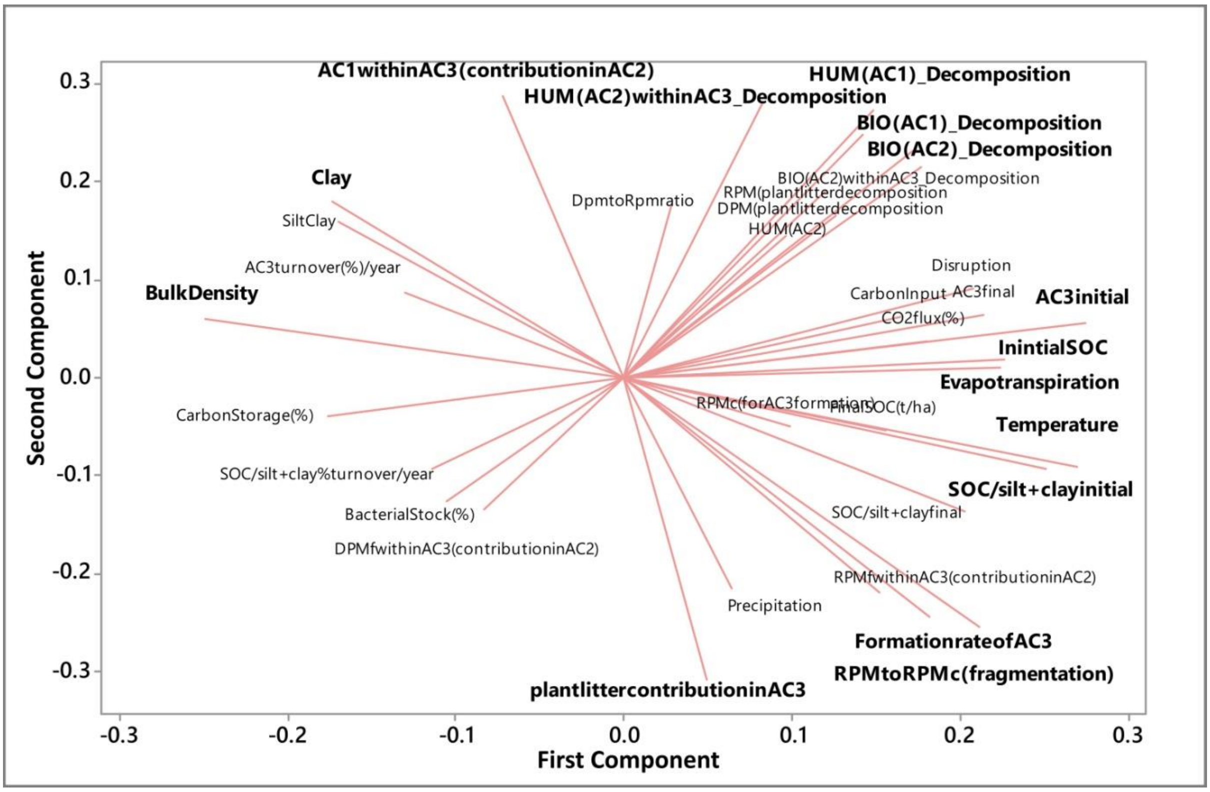


Figure 7

Figure Legends

Figure 1: Geographic distribution of the seven simulated sites (Google Earth, 2016)

Figure 2: Schematic representation of WSA formation modified from Stamati et al. (2013). The

particulate components that make up aggregates are not drawn to relative scale of their physical size.

Figure 3: Schematic representation of aggregation process, aggregate fractions and C pools included in the CAST model. The 3 large hexagons representing the AC1 macro-aggregate pool show in sequence, from top to bottom, 3 stages of macro-aggregate transformation from initial POM entering the soil, until it is decomposed resulting in breakup and release of AC2 and AC3 aggregate fractions.

Figure 4: Study sites placed on a temperature gradient representing different stages of soil evolution from soil formation to soil degradation, including soil restoration. The ordering of sites according to soil formation/degradation pathway also coincided with the temperature gradient.

Figure 5a: Calibration results of Koiliaris CZO (agricultural), Clear Creek (agricultural), Marchfeld CZO (all managements) and Slavkov Forest simulations for the SOC stock distribution together with the field (measured) data used for the calibration. Regarding the goodness of fit of the calibration of the model, the mean RMSE for the SOC is 0.55, which corresponds to 0.55 t C/ha for the SOC stock distribution in a range of 1.03 to 55 t C/ha

Figure 5b: Calibration results of Koiliaris CZO (agricultural), Clear Creek (agricultural), Marchfeld CZO (all managements) and Slavkov Forest simulations for the WSA distribution together with the field data used for the calibration. Regarding the goodness of fit of the calibration of the model, the mean RMSE for the WSA is 1.29

Figure 6: Score plot of the components PC1 and PC2 of the Principal Component Analysis

Figure 7: Loading Plot of the components PC1 and PC2 of the Principal Component Analysis