# Supplement of

## Biogeochemical model Biome-BGCMuSo v6.2 provides plausible and accurate simulations of carbon cycle in Central European beech forests

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**Table S1** List of abbreviations

| Group | Abbreviation | Explanation | Unit |
|---|---|---|---|
| Calibrated parameters | CLEC | Canopy light extinction coefficient | dim |
| | FLNR | Fraction of leaf nitrogen in Rubisco | dim |
| | MSC | Maximum stomatal conductance | m s$^{-1}$ |
| | Nfix | Nitrogen fixation | kgN m$^{-2}$yr$^{-1}$ |
| | VPDC | Vapor pressure deficit at complete conductance reduction | Pa |
| | Sseff | Effect of soilstress factor on photosynthesis | dim |
| Forest ecosystem | SOILC | Soil carbon stock | kgC m$^{-2}$ |
| | LDaboveC_w | Carbon stock in aboveground wood biomass | kgC m$^{-2}$ |
| | CWDC | Carbon stock in coarse woody debris | kgC m$^{-2}$ |
| | litrC | Carbon stock in litter | kgC m$^{-2}$ |
| | cum_nee | Cumulative Net Ecosystem Exchange | kgC m$^{-2}$ |
| | Cum_NPP | Cumulative net primary production | kgC m$^{-2}$ |
| | cum_gpp | Cumulative gross primary production | kgC m$^{-2}$ |
| | cum_tr | Cumulative total respiration | kgC m$^{-2}$ |
| Site | Elevation | Height above sea level | m |
| | Latitude | Position north of the equator | ° |
| Climate | TRange | Long.term mean annual temperature range | °C |
| | AMTmin | Long-term average minimum temperature | °C |
| | AMTday | Long-term mean annual daylight temperature | °C |
| | AMTmean | Long-term mean annual temperature | °C |
| | AMPRCP | Long-term mean annual precipitation total | cm |
| | AMVPD | Long-term mean annual vapour pressure deficit | Pa |
| | AMSRAD | Long-term mean photosynthetically active radiation | W m$^{-2}$ |
| | AMDayLen | Long-term mean daylength | s |
| Soil | SoilDepth | Depth of soil | m |
| | Sand01-Sand10 | Sand proportion in soil layer 1-10 | % |
| | SandAver | Average sand proportion in soil | % |
| | Silt01-Silt10 | Silt proportion in soil layer 1 to 10 | % |
| | SiltAver | Average silt proportion in soil | % |
| | Clay01-Clay10 | Clay proportion in soil layer 1 to 10 | % |
| | ClayAver | Average clay proportion in soil | % |
| | SoilpH01-SoilpH10 | Soil reaction in soil layer 1-10 | dim |

*Description of simulation steps*

Simulations are performed in three steps: (1) spin-up run, (2) transient run, (3) normal run.

Spin-up is a self-initialisation procedure that generates the initial state of the ecosystem using the information about the site, soil, and vegetation type. The spin-up starts from the bare ground with no soil organic matter, a small amount of carbon in leaves, and 50% soil water saturation (which can be set in INI file). During spinup, constant or annually varying regular mortality and fire mortality are allowed, while no management interventions are simulated. A spin-up run lasts several hundred to several thousand years during which carbon stock in an ecosystem is accumulated until a steady state is achieved in soil, when the simulation stops (Thornton and Rosenbloom 2005; Merganičová and Merganič 2014).

A transient run bridges the spin-up and normal runs to avoid the undesired behaviour of simulation outputs due to the sudden changes in $CO_2$ and N-deposition between the two runs (see, for example, (Hidy et al., 2021). During the transient run, constant or annually varying regular natural mortality and fire mortality and management interventions are allowed. It typically lasts several decades, while the length is pre-defined by a user.

A normal run simulates the development of the current target ecosystem (or a future scenario), and it is used to address different research questions, for example, the impact of different climate, N deposition and/or management scenarios on the simulated ecosystem including temporal changes in $CO_2$, and N -deposition on growth. Its length, mortality and management settings depend on user´s requirements.

Table S2 Overview of data sources in the database per country and data group. X indicates that data are available for all sites in the specific country, (X) indicates that the data are available for some plots

| Original data source group | Country | Country abbreviation | Number of plots based on the dominant species | | | | Available data for simulations | | | | | | Number of plots |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Beech | Oak | Norway spruce | Other | Growing stock | Site characteristics | Soil attributes | Climate data | Management | Physiological measurements | |
| Highly instrumented sites (HIS) | Croatia | HR | | 1 | | | X | X | X | X | X | X | 1 |
| | Czechia | CZ | | | 1 | | X | X | X | X | X | X | 1 |
| | Slovakia | SK | 1 | | 1 | | X | X | X | X | X | X | 2 |
| ICP Forests | Croatia | HR | 3 | 3 | | 1 | X | X | (X) | (X) | (X) | | 7 |
| | Czechia | CZ | 3 | 1 | 7 | 4 | X | X | X | X | X | | 15 |
| | Hungary | HU | 3 | 5 | 3 | 6 | X | X | (X) | | | | 17 |
| | Poland | PL | 2 | 2 | 3 | 3 | X | X | (X) | | | | 10 |
| | Slovakia | SK | 4 | 2 | 4 | 1 | X | X | X | X | X | | 11 |
| Silvicultural trials | Czechia | CZ | 1 | 4 | 18 | | X | X | (X) | | X | | 23 |
| Total | | | 17 | 18 | 37 | 15 | | | | | | | 87 |
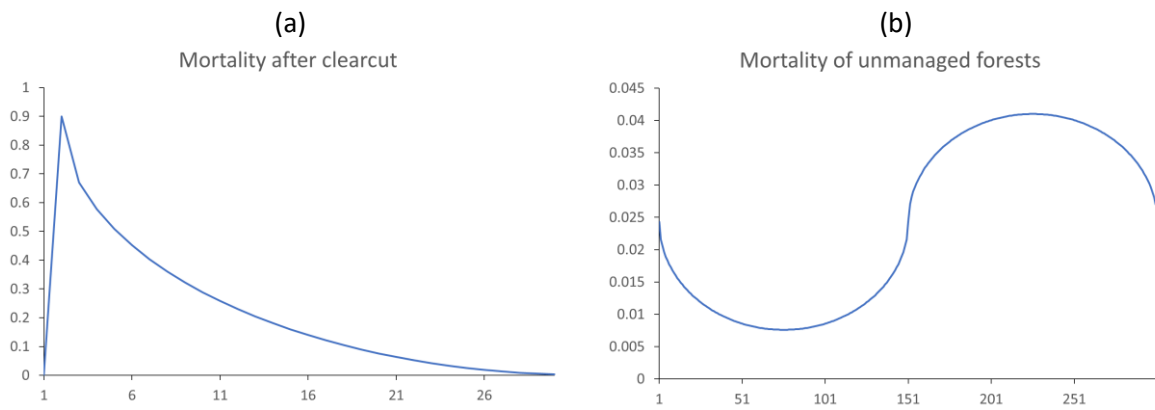
Figure S1 Dynamic mortality rates applied to simulate natural mortality of regeneration after clearcut (a) based on the compiled information on the survival rates of regeneration from experimental studies focusing on European beech (Hülsmann et al., 2018; Barna et al., 2011) and mortality rates of unmanaged forests (b) simulated using an elliptical function (Merganičová and Merganič, 2014).
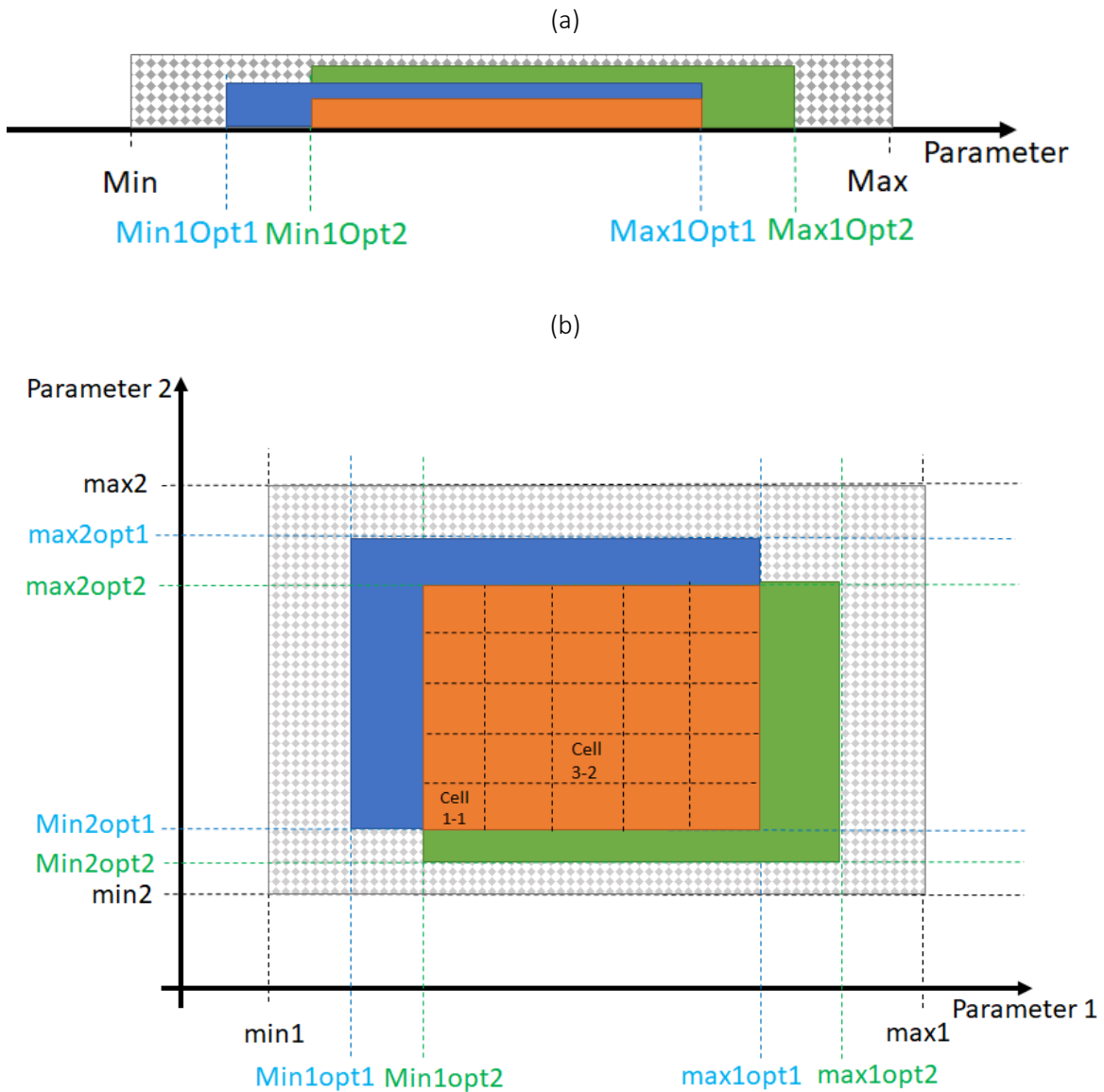
**Figure S2** Identification of feasible parameter ranges per site using a multivariate approach (a) and of multi-site and multivariate optimised (MSMV) parameter values and their parameter ranges (b) on an example of 2D parameter space and the site-specific optimised parameter ranges of two sites. Colours refer to specific variables (a) and sites (b). Min = minimum, Max = maximum, Opt = optimised, area with grey dotted pattern indicates the tested parameter interval (a) or 2D parameter space (b), blue area = optimised parameter interval for variable 1 (a) or 2D space for site 1 (b), green area = optimised parameter interval for variable 2 (a) or 2D parameter space for site 2 (b).
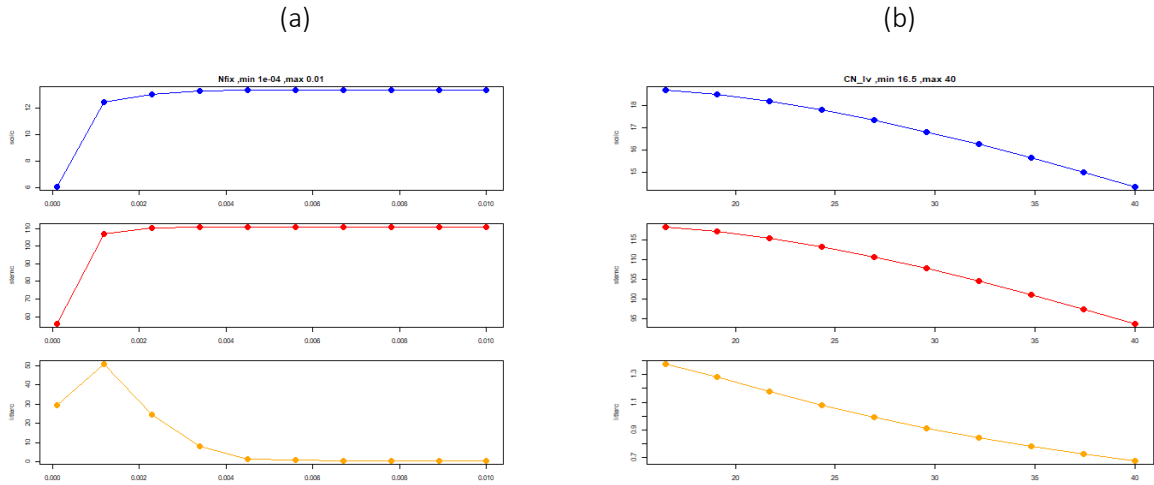
**Figure S3** Impact of nitrogen fixation Nfix (a) and C:N ratio in leaves (b) on carbon stock in soil, aboveground wood, and litter (SoilC, AbgwC, and LitterC, respectively; all in kgC/m$^2$) along the whole tested parameter ranges.
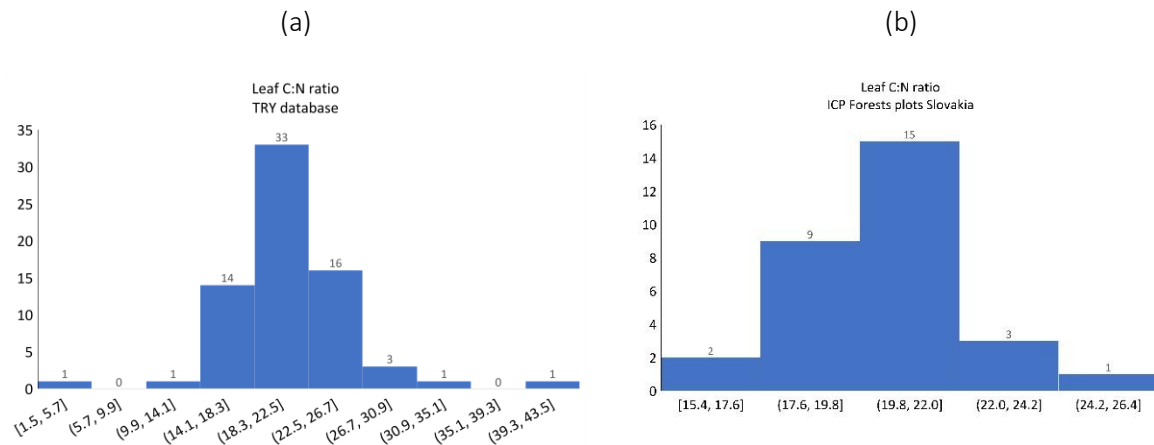
**Figure S4** Histograms of C:N ratios in leaves derived from the TRY (Kattge et al., 2020) database (a) and measurements performed at ICP Forests plots in Slovakia (b).
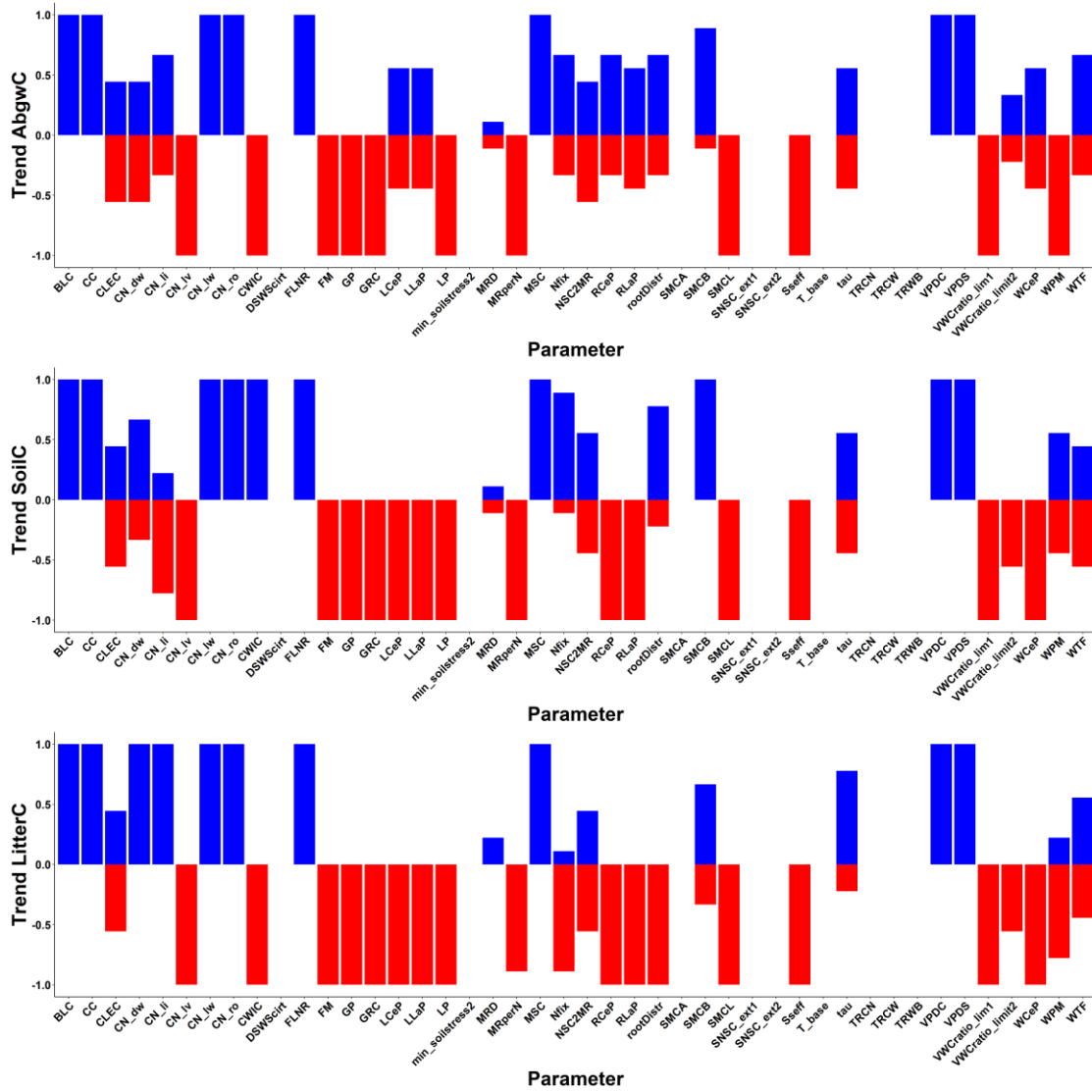
**Figure S5** Analysis of trends in variable change with regard to the increasing value of parameters. Blue colour indicates that increasing the parameter value causes an increase in the particular output variable, while the red colour indicates the reduction of the output variable with the increasing parameter value. If both blue and red columns occur above each other for one parameter, the increase of the parameter value resulted in both increasing and decreasing values of the output variable. The trend value gives the proportion of increasing and decreasing values. AbgwC, SoilC, and LitterC stands for carbon stock in aboveground wood, soil, and litter, respectively.
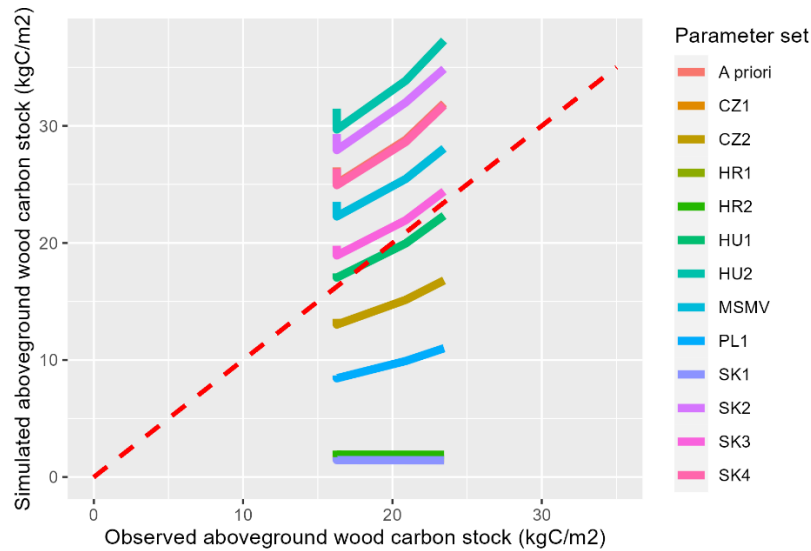
**Figure S6** Comparison of observed and simulated carbon stock in the aboveground wood (AbgwC) using a priori, site-specific (indicated by site identifications), and multi-site (MSMV) optimised sets of ecophysiological parameters for HU1 calibration site. The colours indicate sets of ecophysiological parameters that were used for simulations with BBGCMuSo. The red dashed line represents 1:1 line, when the simulated AbgwC is equal to the observed AbgwC.
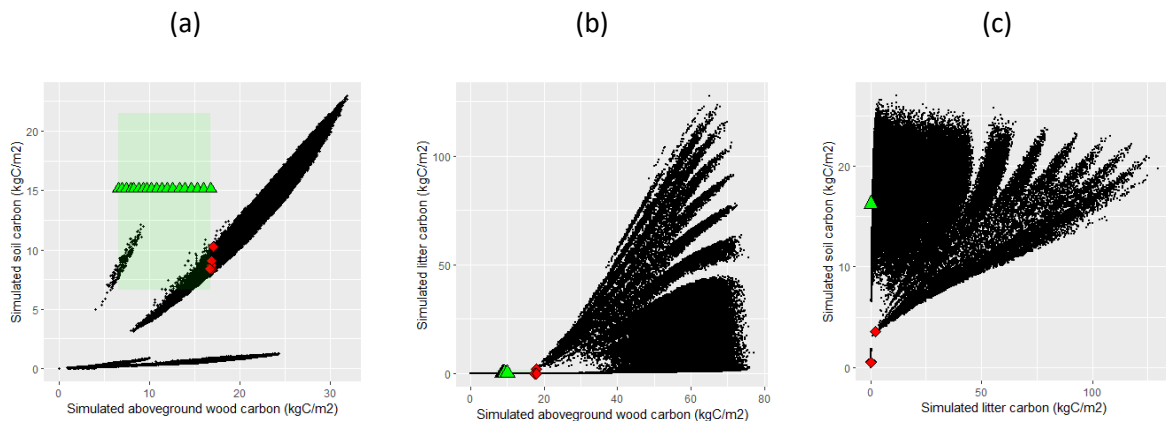
**Figure S7** Relationships between modelled carbon stock in aboveground wood (AbgwC), soil (SoilC), and litter (LitterC) based on 100,000 Monte Carlo simulations performed for one site during the calibration process. Black dots represent individual simulations, red diamonds represent the best 25 variants selected based on the calculated AbgwC likelihood during GLUE calibration. Note that SoilC and LitterC are represented by mean values over the whole normal run simulations, while AbgwC is represented by the maximum value (hence the value from the last year of simulations), because normal run simulations started with zero AbgwC due to the simulated clearcutting at the beginning. Green triangles represent field observations of respective variables, while SoilC was measured only once, hence this value was taken as a constant to plot all observed AbgwC values. The green rectangular area represents the space defined by field observations of AbgwC and variable ranges of SoilC and LitterC reported in the literature (Pavlenda and Pajtík, 2010).
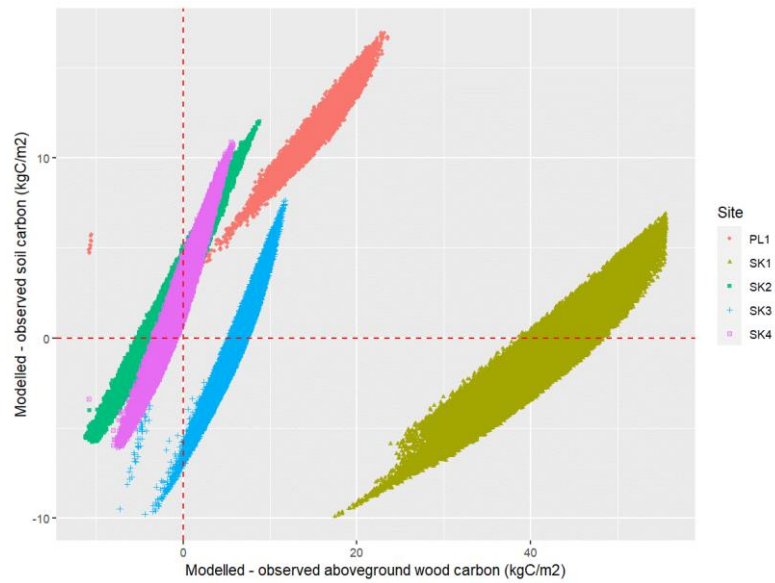
**Figure S8** Relationships between mean differences of carbon stock in aboveground wood (AbgwC) and soil (SoilC) calculated as arithmetic means of the modelled value minus the observed value of the respective variable in the particular years. The modelled data come from site-specific Monte Carlo simulations used for model calibration. Colours represent individual sites, for which the observed values of both AbgwC and SoilC were available. Red lines indicate zero differences between modelled and observed values.
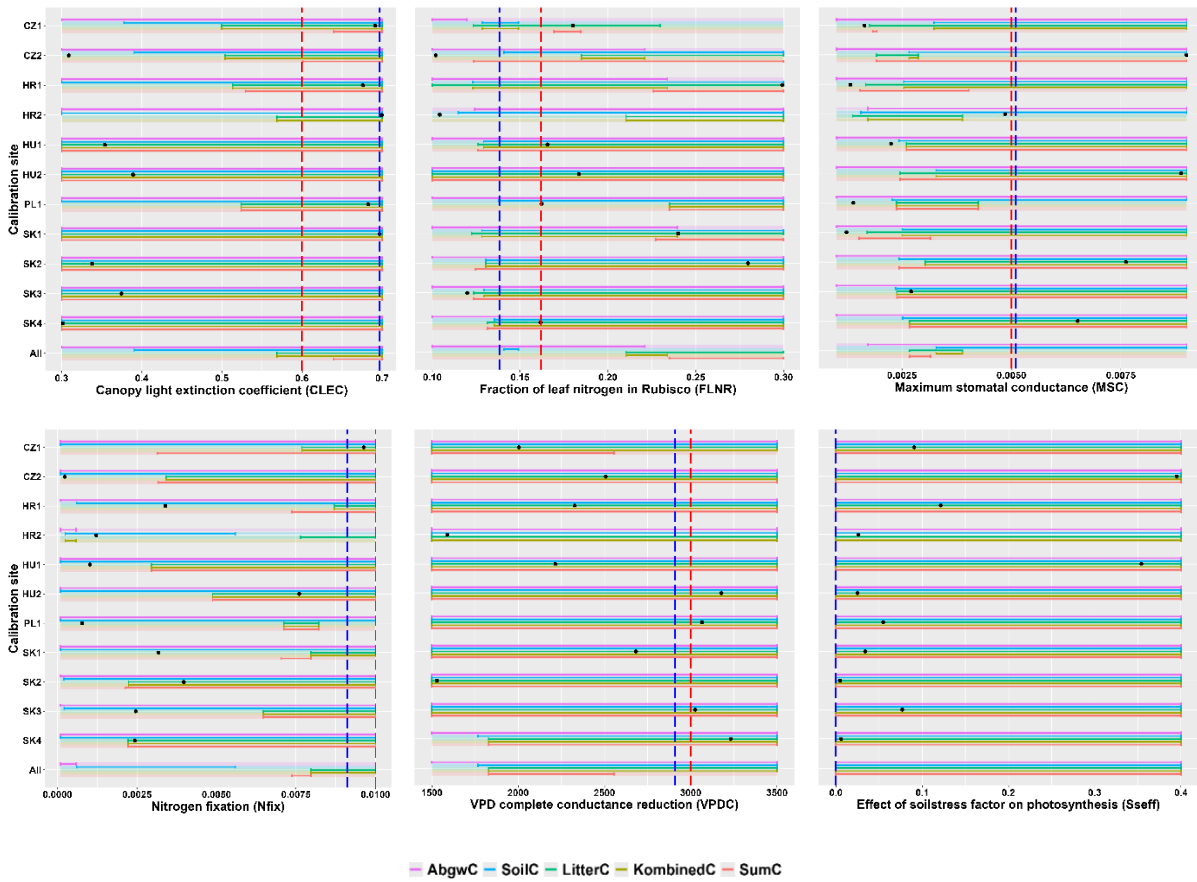
**Figure S9** Robustness test of calibrated site-specific and multi-optimised parameter values based on decision tree analysis. Black dots are site-specific optimised parameter values, vertical red and blue lines represent the a priori and the multi-site optimised values, respectively. Background transparent coloured horizontal lines represent the tested parameter range, while non-transparent coloured lines show the optimised parameter ranges based on decision trees performed for carbon stock in aboveground wood (purple), soil (blue), and litter (green). The khaki interval is an optimised parameter range derived as an intersection of the three ranges for individual variables defined above. The red interval in an optimised parameter range derived for the sum of the three carbon stocks. If the optimised ranges for individual variables or sites did not overlap, the final range was derived based on the prevailing intersections.
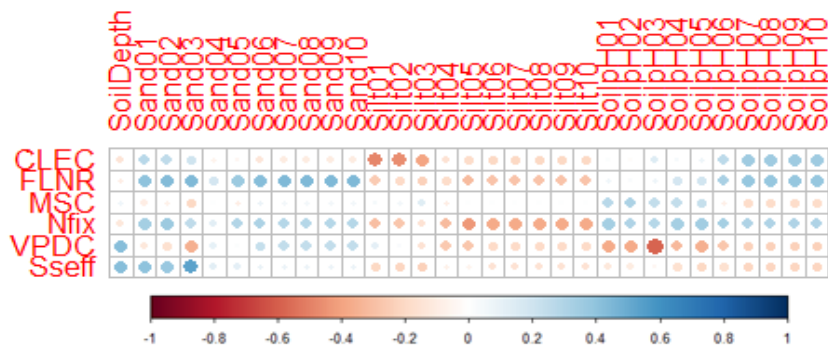
**Figure S10** Spearman correlations of site-specific optimised parameter values to soil characteristics. The colour and the size of the circles indicate the value of the correlation coefficient. Abbreviations of parameters and environmental characteristics are in **Table S1**.
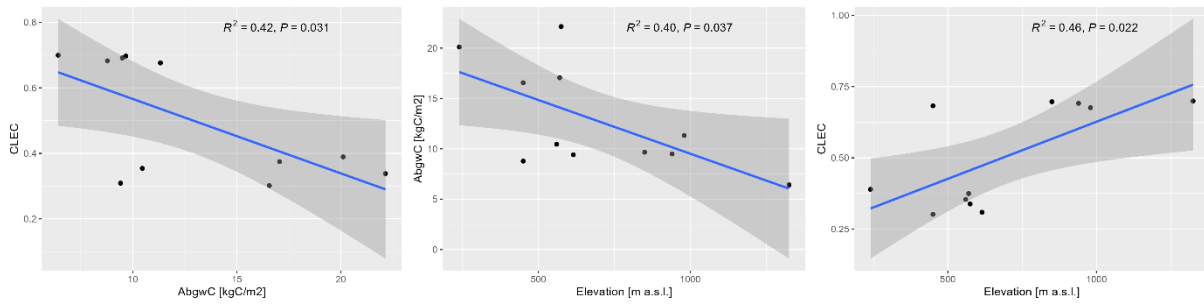
**Figure S11** Linear regressions between site-specific optimised values (SSMV) of canopy light extinction coefficient (CLEC) and carbon stock in the aboveground wood at the standardised age of 63 years (AbgwC) and elevation of 11 calibration sites.

(a)                                  (b)                                  (c)
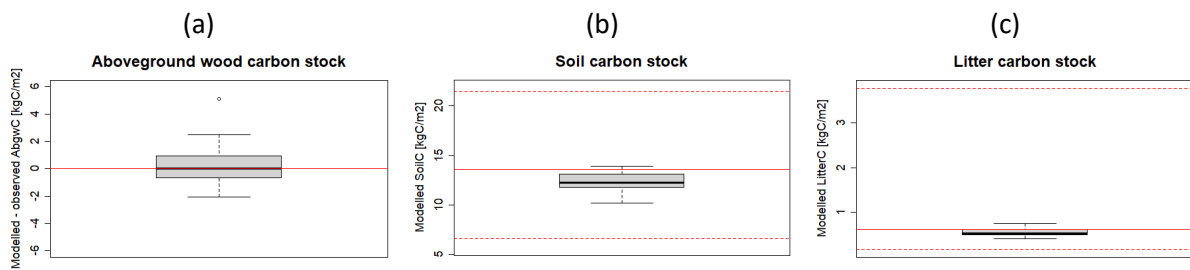
**Figure S12** Validation of multi-sites multivariate optimised parameter set based on the simulations of 8 research sites. The figures represent boxplots of the differences between the modelled and observed aboveground wood carbon stock (AbgwC, a), and modelled carbon stock in soil (SoilC, b) and litter (LitterC, c) compared to ranges observed in the field (horizontal red lines represent median (solid line) and 5 and 95% percentiles (dashed lines)). The ranges for carbon stock in soil and litter were taken from **(Pavlenda and Pajtík, 2010)**. The thick horizontal lines of boxplots represent medians, boxes represent the interquartile ranges (IQR), and the vertical lines represent ±1.5IQR.

(a)                                  (b)                                  (c)
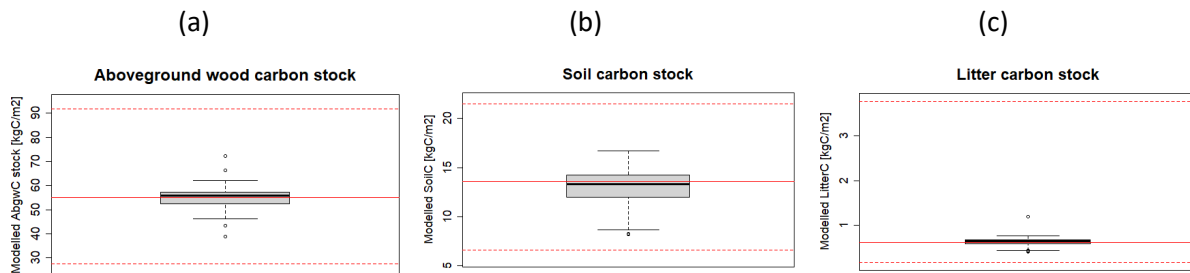
**Figure S13** Plausibility of carbon simulated content in aboveground wood, soil and litter (AbgwC, SoilC, LitterC) at the end of spinup simulations performed for all sites in comparison to ranges derived from the literature (horizontal red lines represent median (solid line) and 5 and 95% percentiles (dashed lines)). The ranges for carbon stock in the aboveground wood were taken from **(Barna et al., 2011)** for over-aged beech forests at average-quality sites. The ranges for carbon stock in soil and litter were taken from **(Pavlenda and Pajtík, 2010)**.
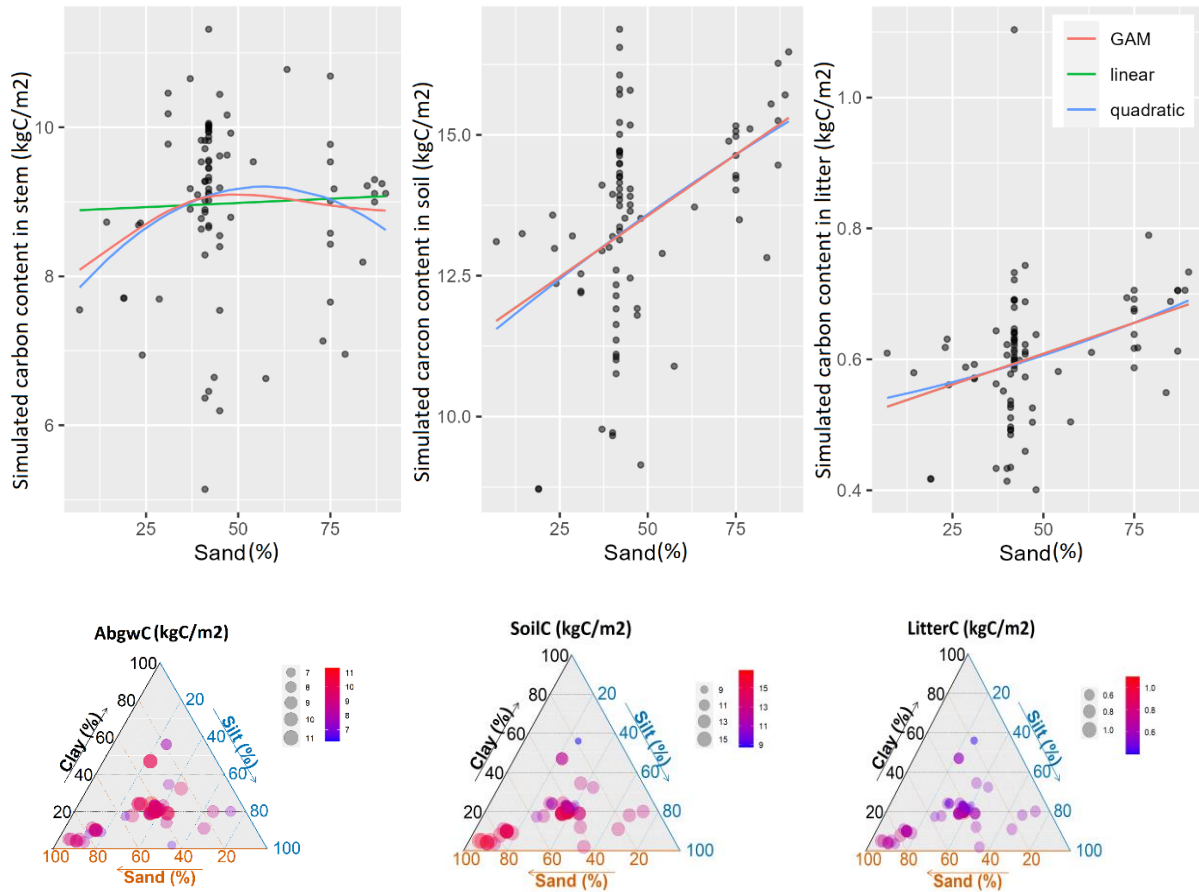
**Figure S14** Responses of modelled carbon stock in the aboveground wood (AbgwC) at the standardised stand age of 35 years (left), soil (middle) and litter (right) carbon stocks to sand content in soil (top) and soil texture (bottom). The simulations with BBGCMuSo were conducted for 87 sites distributed across central Europe (see **Chyba! Nenašiel sa žiaden zdroj odkazov.**).
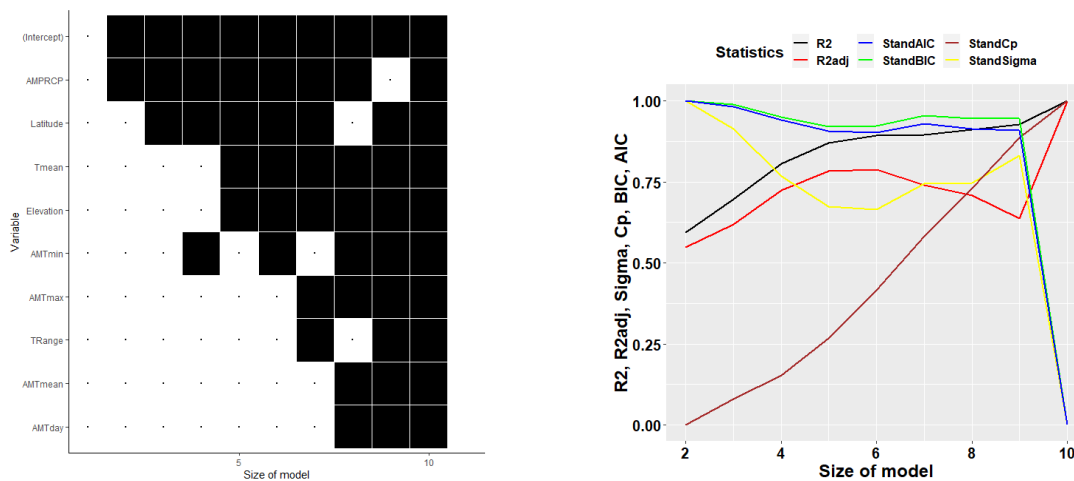
**Figure S15** Multiple linear regressions explaining the variation in site-specific canopy light extinction coefficient (CLEC) values using different combinations of environmental characteristics. The size of the model represents the number of predictors included in the multiple regression model. The figure on the left presents the selected combinations of environmental characteristics, while black squares indicates, which characteristics are included in multiple regression models and black dots indicate their absence in the model. The right figure shows statistical characteristics of derived models as follows: R2—R-squared, R2adj—adjusted R-squared, AIC—AKAIKE information criterion, BIC—Bayesian information criterion, Cp—Mallows' statistic, Sigma—residual standard deviation. The abbreviations of environmental characteristics are explained in **Table S1**.
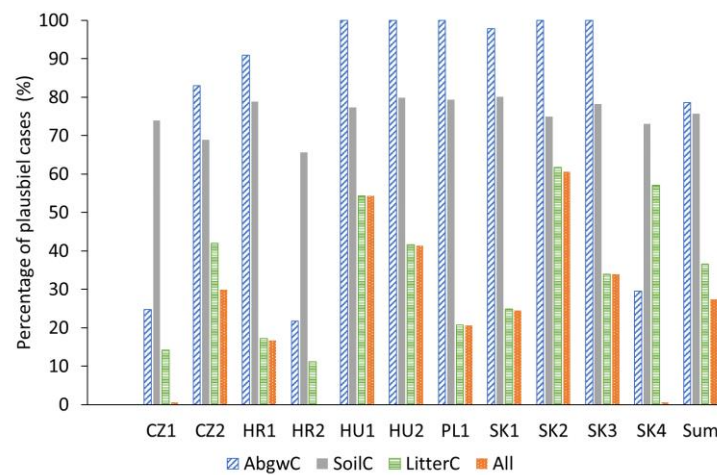
**Figure S16** Plausibility percentages of BBGCMuSo simulations per calibration site and carbon stock in aboveground wood, soil, litter and all output variables at the same time (AbgwC, SoilC, LitterC, All).
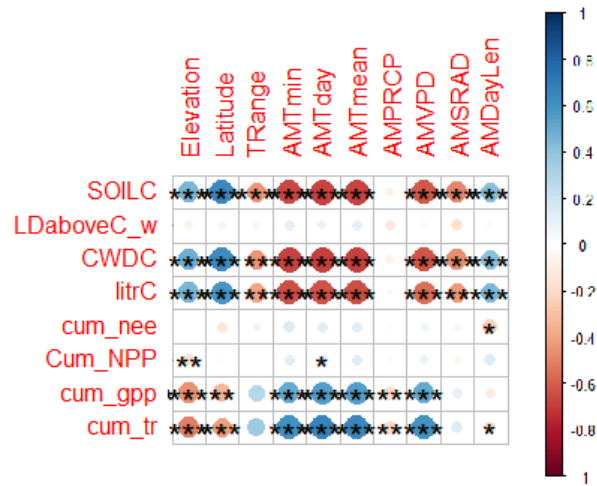
**Figure S17** Spearman correlations between selected carbon-related output variables and site characteristics. The colour and the size of the circles indicate the value of the correlation coefficient, and the stars indicate the significance of the correlation (1 star, 2 stars and 3 stars represent 95%, 99% and 99.9% significance levels, respectively). The abbreviations are explained in **Table S1**.
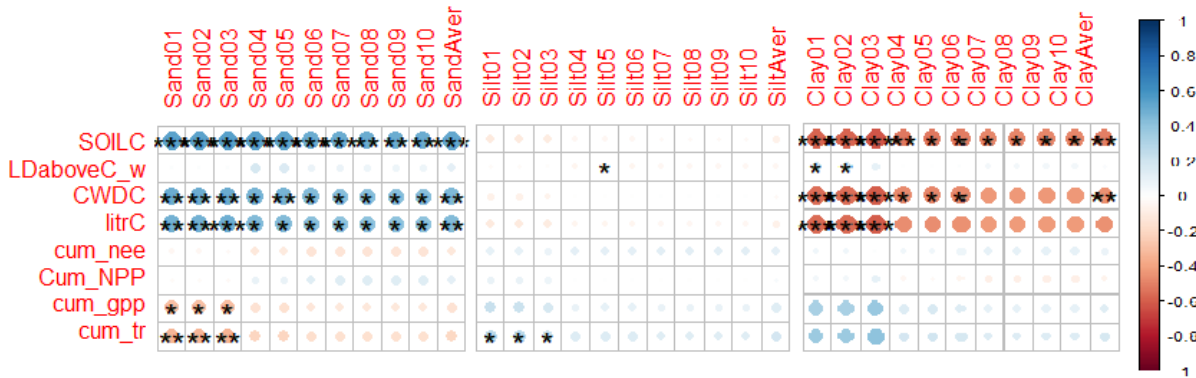
**Figure S18** Spearman correlations between selected carbon-related output variables and soil particle proportions in individual soil layers. The colour and the size of the circles indicate the value of the correlation coefficient, and the stars indicate the significance of the correlation (1 star, 2 stars and 3 stars refer to 95%, 99% and 99.9% significance levels, respectively). The abbreviations are explained in **Table S1**. Values behind soil particle groups indicate individual soil layers, while Aver refers to the mean value calculated from all layers.
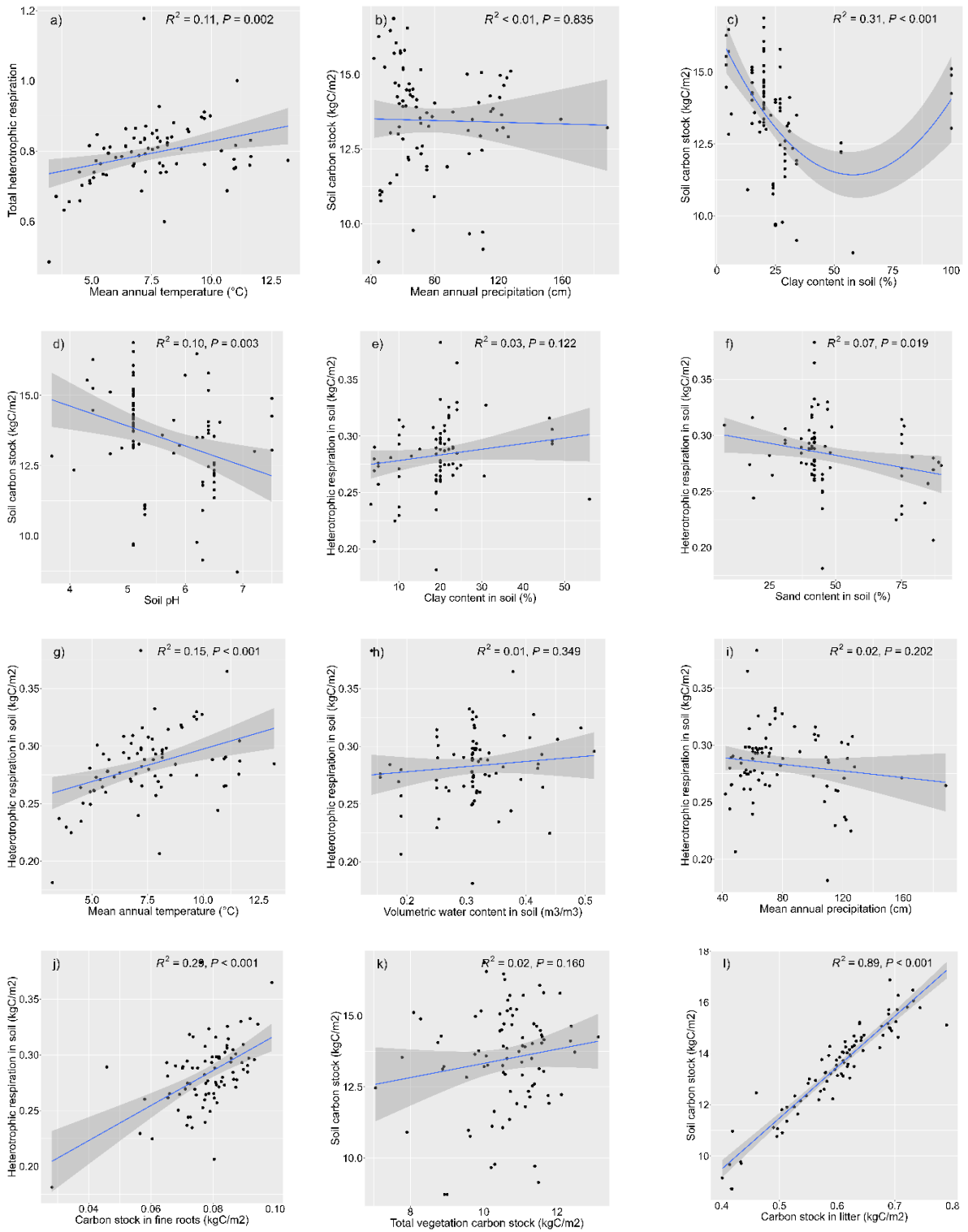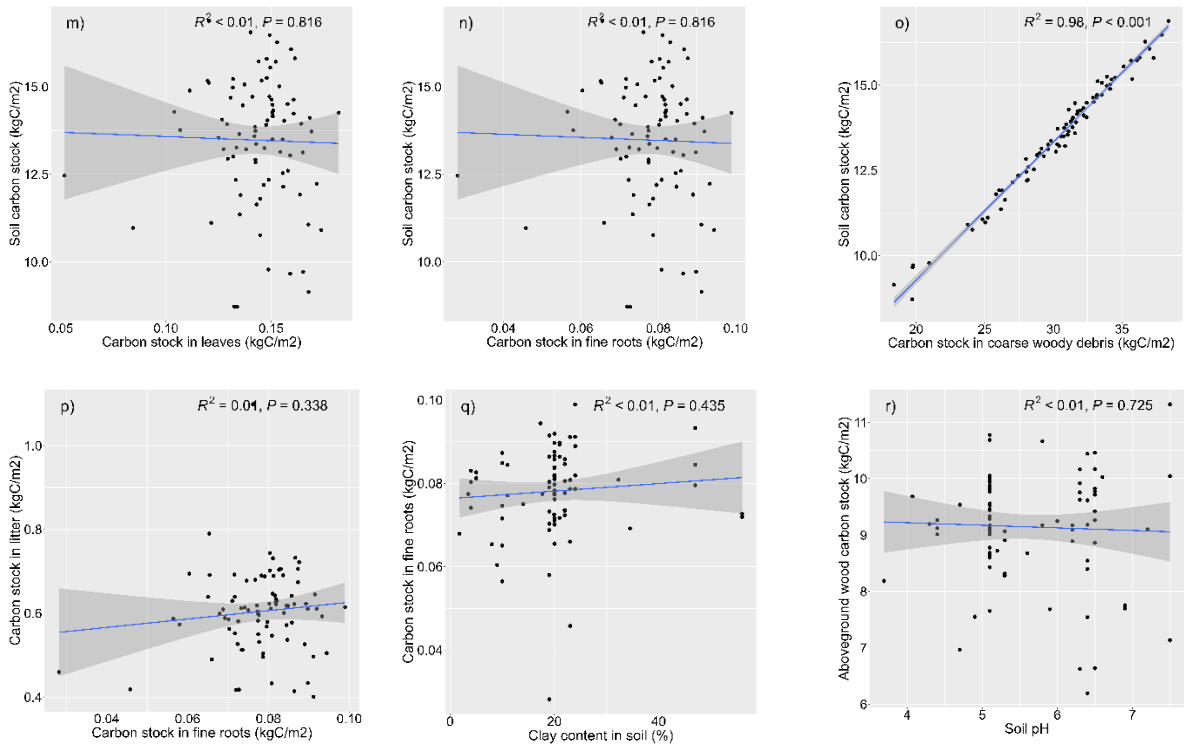
**Figure S19** Relationships between selected output variables and environmental characteristics derived from the BBGCMuSo simulated output of 87 sites distributed across central Europe (see **Chyba! Nenašiel sa žiaden zdroj odkazov.**).
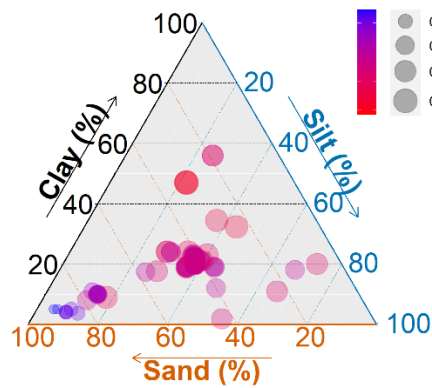
**Figure S20** Relationships between the simulated volumetric soil water content and soil texture based on the BBGCMuSo simulated output of 87 sites distributed across central Europe (see **Chyba! Nenašiel sa žiaden zdroj odkazov.**).

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