Izvirni znanstveni članek / Original scientific paper

ASSESSMENT OF ORGANIC MATTER CHANGES IN THE SOIL OF THE BRDO PLOT UNDER DIFFERENT CLIMATE CHANGE SCENARIOS THROUGH THE YASSO07 MODEL APPLICATION

OCENA SPREMEMB ORGANSKE SNOVI V TLEH NA PLOSKVI BRDO GLEDE NA RAZLIČNE SCENARIJE PODNEBNIH SPREMEMB Z UPORABO MODELA YASSO07

Milan KOBAL[1], Klemen ELER[2], Primož SIMONČIČ[3], Hojka KRAIGHER[4]

(1) Gozdarski inštitut Slovenije, Večna pot 2, SI-1000 Ljubljana, Slovenija, milan.kobal@gozdis.si

(2) Oddelek za agronomijo, Biotehniška fakulteta Univerze v Ljubljani, Jamnikarjeva 101, SI-1000 Ljubljana, Slovenija, klemen.eler@bf.uni-lj.si

(3) Gozdarski inštitut Slovenije, Večna pot 2, SI-1000 Ljubljana, Slovenija, primoz.simoncic@gozdis.si

(4) Gozdarski inštitut Slovenije, Večna pot 2, SI-1000 Ljubljana, Slovenija, hojka.kraigher@gozdis.si

ABSTRACT

The forest soil can act as an important sink for CO_2 and in that respect also appears in the national Kyoto reports, where a distinction is made between carbon accumulated in litter and organic soil horizons and carbon accumulated in mineral soil layers. There is a multitude of dynamic models of organic carbon (C_{org}) change in the soil particularly due to different environmental and anthropogenic factors. The purpose of this paper is the Yasso07 model application on the “Brdo” plot, which is part of the ICP Forest Level II plots of Slovenia. The Yasso07 model describes the decomposition of organic matter in the forest soil by dividing litter inputs into different components with varying decomposition rates. Here, the temporal change of soil C_{org} in various scenarios of future climate change (increase in air temperature, change in precipitation) was predicted. The difference between the measured amount and the model-predicted amount of C_{org} in the soil for the current climate on the Brdo plot is 6.4 t C ha^{-1} (88.6 t C ha^{-1} measured vs. 95.0 t C ha^{-1} predicted). Taking into consideration the climate change scenarios for Slovenia, C_{org} stock is expected to decrease in the future according to Yasso07 projections in all scenarios of climate change. The estimate of 100-year decrease of C_{org} is the largest for scenario, when large increase of both temperature and precipitation is expected (18.2%) and smallest when small temperature increase and precipitation decrease are predicted (9.3%). Assuming stable litter input, larger influence on C_{org} decrease was predicted for the temperature change compared to precipitation change. However, many uncertainties are included in model estimates ranging from litter input estimates, climate change uncertainties, climate-litter production feedbacks, starting value estimates, etc. The determination of the uncertainty of model calculations is a requirement for conducting simulations and their interpretation.

Key words: litter decomposition, litter components, soil carbon, model uncertainty, Slovenia

IZVLEČEK

Gozdna tla lahko delujejo kot pomemben ponor za CO_2 in v zvezi s tem se pojavljajo tudi v nacionalnih poročilih Kjota, kot skladišče organskega ogljika organskega ogljika (C_{org}) v organskem in mineralnem delu tal. Obstaja množica dinamičnih modelov sprememb C_{org} v tleh predvsem zaradi različnih okoljskih in antropogenih dejavnikov. Namen tega prispevka je uporaba modela Yasso07 na ploskvi “Brdo”, ki je del ICP Forest ploskev intenzivnega spremljanja stanja gozdov. Model Yasso07 opisuje razgradnjo organskih snovi v gozdnih tleh z deljenjem vnosov opada v tla z različnimi stopnjami hitrosti razgradnje. V prispevku prikazujemo časovno spremembo zalog C_{org} v tleh glede na različne scenarije prihodnjih podnebnih sprememb (povečanje temperature zraka, spremembe v padavinah). Razlika med izmerjeno vrednostjo in vrednostjo modela, napovedano za C_{org} v tleh pri trenutnih razmerah na ploskvi Brdo, je 6,4 t C ha^{-1}(88,6 t C ha^{-1} merjeno proti 95,0 t C ha^{-1} napovedano). Ob upoštevanju scenarijev podnebnih sprememb za Slovenijo je na podlagi modela Yasso07 pričakovati zmanjšanje zalog C_{org}. Ocena za 100-letno zmanjšanje C_{org} je največja pri scenariju, kjer se pričakuje velik porast tako temperature kot padavin (18,2 %), in najmanjši, ko je predvideno majhno povečanje temperature in majhno zmanjšanje padavin (9,3%) . Ob predpostavki stabilnega vhod opada je opaziti večji vpliv temperature na napovedano zmanjšanje C_{org}. Upoštevati je treba veliko negotovost glede ocene vnosa opada, ocene podnebnih sprememb, ocene začetnih vrednosti itd. Določitev negotovosti modelnih izračunov je pogoj za opravljanje simulacij in njihovo razlago.

Ključne besede: razgradnja opada, sestava opada, ogljik v tleh, negotovost, Slovenija

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1 INTRODUCTION

1 UVOD

Forests, covering 61.1% ± 0.7% of the entire surface of Slovenia (HLADNIK and ŽIŽEK, 2012), can act as an important organic source or sink of organic carbon (C_{org}) (LISKI et al., 2006). The importance of forests as a sink/source of organic carbon is recognized in the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. The Kyoto Protocol signatory countries have made a commitment to (voluntarily) include the changes in organic carbon occurring as a result of deforestation, reforestation (Article 3.3), and forest management (Article 3.4), in their annual reports, for all five organic carbon collectors in forest ecosystems (see KOBAL et al., 2012).

The forest soil acting as a sink of C_{org} appears in the national reports in the chapter about C_{org} in litter and in the chapter about C_{org} in the mineral part of the soil. Despite the significance or role which the forest soil plays in the bonding of carbon, and as a result in the Kyoto Protocol, there is no common methodology available for monitoring the changes of non-living organic matter (LISKI et al., 2006), which, according to the definitions of the Kyoto Protocol, also includes litter and organic material in forest soil. Also most of national forest inventories do not include measurements of changes in carbon presence in forest soil (TOMPPO et al., 2010). Another difficulty regarding the assessment of C_{org} content in the forest soil is the spatial variability in forest sites: the expected time changes are lesser than the spatial variability of the stock of C_{org} in forests (LISKI, 1995; LISKI et al., 1998; TUOMI et al., 2011). Alternative solutions are model calculations, which are often used for assessment of the stock of C_{org} in forest soil and the changes thereof (PELTONIEMI et al., 2006; PELTONIEMI et al., 2007; MÄKIPÄÄ et al., 2008).

There is a multitude of dynamic models of C_{org} cycling in the soil, which are used in the context of monitoring of changes in C_{org}, e.g. CENTURY (PARTON et al., 1987), RothC (COLEMAN and JENKINSON, 1996); SOILN (ECKERSTEN et al., 1998); ROMUL (CHERTOV et al., 2001), Yasso or the newer version Yasso07 (LISKI et al., 2005; TUOMI et al., 2009, LISKI, 2009) and ANAFORE (DECKMYN et al., 2008). The models vary by complexity and the necessary quantity of input data (PELTONIEMI et al., 2007). Yasso07 and RothC are considered to be relatively simple models, while for example ROMUL is a more complex model of circulation of C_{org} in the forest soil, requiring a greater number of input data. The purpose of this paper is the experimental application of the Yasso07 model on the "Brdo" plot, which is included in the network of intensive monitoring of forests in Slovenia since 2003, and comparison of the results of change of the quantity of organic matter in the soil depending on various future changes in air temperature and precipitation.

2 MATERIALS AND METHODS

2 MATERIALI IN METODE

2.1 The plot Brdo

2.1 Ploskev Brdo

The plot Brdo is one of ten plots subject to intensive monitoring of Slovenian forests (Level II), located on the Brdo pri Kranju site (www.brdo.si). The 1-hectare site was established in 2003. The central part of the plots, where intense measurements are taking place, measures 50 x 50 meters. The bedrock is gravel, soils are dystric brown soil. The plot hosts a secondary acidophilic 120-year old Scots pine forest (*Pinus sylvestris*) with blueberry (*Vaccinio myrtilli - Pinetum*); the assumed primary (native) forest consisted of sessile oak and hornbeam with blueberry shrubs, degraded in the past by constant litter gathering, excessive opening of forest stands and selective intensive cutting of deciduous trees. The share of deciduous trees has gradually decreased over the last century, and today the plot prevalently hosts Scots pine, while sessile oak, sweet chestnut and spruce appear only as isolated trees. The average age of trees present on the plot is around 120 years.

2.2 Yasso07 Model

2.2 Yasso07 Model

The Yasso07 model describes the decomposition of organic matter in the forest soil (TUOMI et al., 2009; 2011) and is an upgraded version of the previous Yasso model (LISKI et al., 2005), as it was developed on a larger number of input data and uses more advanced mathematical formulae (TUOMI et al., 2008). The Yasso07 model is based on three premises regarding the decay decomposition of organic matter (TUOMI et al., 2009; 2011), specifically:

1. The plant litter consists of various components with varying decomposition rates; generally, two components exist: wood and non-wood. Decomposition of wood / woody debris is slower than decomposition of non-wood litter due to lignin content, and also depends on the size of the wood fragments. Both the wood and non-wood biomass consist of four groups of substances (AWEN compounds), each with its own rate of decomposition (mass loss rate), which is independent of the origin of litter:

- substances that are soluble in non-polar solvents, ethanol or dichloromethane (referred to as E),

- water-soluble substances (referred to as W),
- substances hydrolyzing in acid (referred to as A)
- non-soluble substances that do not hydrolize (referred to as N)

2. The mass loss rate of each individual group of compounds depends on the climate, which can be described in a simplified manner with air temperature and precipitation data with any time step.

3. The decomposition processes for individual groups of compounds cause transformation of a certain part of the individual AWEN component into another component (Figure 1) and loss of organic carbon from the soil system in the form of CO_2. A smaller portion of AWEN components produce relatively decomposition-resistant humus (H).

In total, 25 different parameters are included in the Yasso07 model, which were determined through empirical studies of a large number of samples (litterbags) from Europe and North America (TUOMI et al., 2009). The average values of these parameters are known, as well as 95% confidence intervals (TUOMI et al., 2009; 2011; RANTAKARI et al., 2012). These parameters relate to:

- The mass loss rate of the individual AWEN + H component (5 parameters)
- Relative mass flows/transformations from one component to the next (13 parameters)
- Mass loss rate dependence on temperature and precipitation (3 parameters)
- Dependence of decomposition of wooden fragments (branches, roots) on the diameter of these fragments (3 parameters)
- Adjustment for organic mass leaching from the litterbags (1 parameter)

The model works so that all inputs of organic matter into the soil (leaves, branches, stumps, fine and thick roots) are categorized based on the quantity of each AWEN component, adding those figures to the current quantity of the same component already present in the soil. The input data can be acquired based on litterfall measurements or based on the model calculation (percentage of the tree biomass which decays on an annual basis). Applying the known mass loss rate of each component, the sum is then used to predict the remainder of the relevant component after a certain time, and the quantity which transforms during this time either into another AWEN component or humus. The mass loss rate parameters are not fixed, but rather depend on temperature and humidity, and in the case of wooden fragments also on the size (diameter) of the fragment in question. Yasso07 takes the amount of precipitation as substitute data for the humidity of the organic matter in the soil. The model interval can be either one month or one year. Depending on the model interval, we can also adjust the time resolution of input data (temperature, precipitation, litterfall amount).

The result of the Yasso07 model is the total quantity of organic carbon in to a) litter (dead wood, Ol, Of and Oh organic subhorizons) and soil organic matter in mineral part up to a depth of 1 m. The model can also render the change in the quantity of organic carbon or CO_2 emissions from the surveyed soil.

The Yasso07 model also estimates the calculation

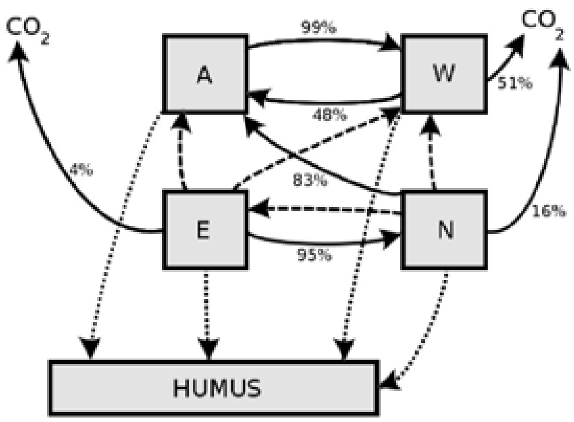

Fig. 1: Illustration of transformation between individual litter components which comprise the basic Yasso07 model. The dotted arrows signify smaller flows, while the dashed arrows depict insignificant flows (modified after TUOMI et al., 2011).

Slika 1: Prikaz transformacije posameznih delov opada, ki predstavljajo osnovo modela Yasso07. Pikčaste puščice pomenijo manjše tokove, medtem ko prekinjene puščice ponazarjajo nepomembne tokove (prilagojeno po Tuomi et al., 2011).

uncertainty, which consists of three components of uncertainty: (1) uncertainty concerning model parameters, (2) uncertainty concerning the quantity of litterfall, and (3) uncertainty concerning the chemical composition of litterfall. The uncertainty of the model parameter is estimated using the Monte Carlo approach, by providing the number of combinations of model parameters. The parameters are selected randomly, in line with the distribution of values for each parameter, and a somewhat different result is calculated for each variant. Different model results from different combinations of parameter values are the uncertainty estimation. The uncertainty regarding the quantity and composition of litterfall is based on measured values.

Yasso 07 is also useful for the simulation of climate change (higher temperature, lower precipitation, changed intra-year distribution of precipitation) or changed soil usage (deforestation, overgrowth). For the latter, we input the share of contraction or expansion of the area of a given habitat into the model, together with the corresponding quantity and composition of litter. In overgrowth we increase the share of forest and decrease the share of grassland/shrub, and in deforestation we decrease the share of forest.

2.3 Preparation of input data for Yasso07
2.3 Priprava vhodnih podatkov za model YASSO07

To start the Yasso07 model, Yasso model requires data about the quantity of litter and its quality (proportions of the aforementioned groups), data about temperatures and precipitation, and data on the starting quantity of C_{org} in the soil. We assume constant productivity of forest in future.

2.3.1 Data about input of organic matter into the soil
2.3.1 Podatki o vnosih organske snovi v tla

We assumed that organic matter can enter into the soil from six different sources on the Brdo plot:

- Above-ground non-wood litterfall, e.g. fallen leaves or needles;
- Above-ground small wood litterfall, e.g. branches and twigs;
- Above-ground large wood litterfall, e.g. trunks of felled trees;
- Below-ground non-wood litterfall, e.g. fine roots;
- Below-ground small wood litterfall, e.g. roots;
- Below-ground large wood litterfall, e.g. stumps;

As we do not yet have detailed information on the amount of litterfall for each source, we took these data from literature, or calculated them based on similar reports (Finish GHG Report). First we used expansion factors for the Scots pine (LEHTONEN et al., 2004) based on the diameter at breast height and we calculated the volume of the tree based on this, then we calculated the amount of dry matter for individual parts of the individual tree, and finally, based on the known tree density per hectare, we recalculated it for the surface area (in t ha^{-1}). However, we have no data on predictive quality of usage of boreal expansion factors for the Alps.

We took the quantity of fine roots from MAKKONEN AND HELMISAARI (2001). Then we used data from literature (FINISH GHG REPORT) to get the portion of the individual part of the tree, which decays each year and represents the input of organic matter into the soil ($litterfall_{input}$), specifically based on the quantity of the same source (W_i) in t ha^{-1} and annual litterfall production (r_i) using the equation $litterfall_{input} = r_i \times W_i$. The share of C_{org} in an individual part of the tree was taken from JANSSENS et al. (1999). Detailed data is presented in Table 1.

For wood litterfall, the Yasso07 model must also include the average size of the litterfall, in terms of diameter. For branches, we assumed the average diameter to be 2 cm; the same diameter was also assumed for roots. For stumps we assumed the average diameter to be 10 cm. The proportion of AWEN components for the Scots pine was taken from literature (SYKE, 2011).

2.3.2 Climate data
2.3.2 Klimatski podatki

To start, the Yasso07 model requires data about average monthly or annual air temperature, average temperature amplitude (average half of the difference between the warmest and coolest months in the year) and average monthly or annual amount of precipitation. Climate data were acquired from the ARSO website (http://meteo.arso.gov.si), specifically for the Brnik airport for the 1986-2012 period, as it is located relatively close to the Brdo plot. The average annual quantity of precipitation is 1,326.2 mm, the average annual temperature is 9.4°C, and the average annual temperature amplitude is 11.3°C. Average monthly values are presented in Table 2.

Changes in the quantity of precipitation and air temperatures during the 21st century were taken from projections of the changes in the quantity of precipitation and average air temperature, which were prepared by BERGANT (2003) for Slovenia, and which have already been used in forestry on the example of the expected redistribution of vegetation types (KUT-

Table 1: Dry mass data (t ha^{-1}), annual production of litterfall r_r and input into the floor (t ha^{-1} year^{-1} or t C ha^{-1} year^{-1}) for individual parts of Scots pine *Pinus sylvestris* (data compiled and recalculated from ref: LEHTONEN et al., 2004; MAKKONEN AND HELMISAARI, 2001; JANSSENS et al., 1999)

Preglednica 1: Podatki o suhi masi (t ha^{-1}), letna proizvodnji opada r_r in vnos v tla (t ha^{-1} leto^{-1} ali t C ha^{-1} leto^{-1}) za posamezne dele rdečega bora *Pinus sylvestris* (podatki so zbrani in preračunani iz LEHTONEN et al., 2004; MAKKONEN AND HELMISAARI, 2001; JANSSENS et al., 1999)

	Trunks Debla	Leaves Listi	Branches Veje	Dead branches Odmrle veje	Stumps Panji	Thick roots Debele korenine	Roots Korenine	Fine roots Drobne korenine
Dry mass [t ha^{-1}] Suha masa [t ha^{-1}]	73.20	26.48	23.94	4.78	9.86	8.22	17.15	0.86
r_i	0.00	0.25	0.02	0.50	0.02	0.02	0.02	0.85
Input into the soil [t ha^{-1} year^{-1}] Vnos v tla [t ha^{-1} leto^{-1}]	0.00	6.49	0.48	2.39	0.20	0.15	0.32	0.00
C_{org} concentration [%] C_{org} koncentracija [%]	48.9	48.2	51.6	51.6	48.9	49.4	52.6	55.4
Input in to the soil [t C ha^{-1} year^{-1}] Vnos v tla [t C ha^{-1} leto^{-1}]	0.00	3.13	0.25	1.23	0.04	0.10	0.08	0.47
Entrance for Yasso07 [t C ha^{-1} year^{-1}] Vhod v model Yasso07 [t C ha^{-1} leto^{-1}]	**0.00**	**3.13**	**1.48**		**0.10**	**0.24**		**0.47**

NAR et al., 2009). Bergant's calculations show mainly a marked increase in air temperature in the warm half of the year, compared to the colder half of the year, and a decrease in the amount of precipitation during the warmer half of the year, as well as an increase in precipitation during the cooler half of the year. In the 21st century, the most intensive warming was recorded in the summer (June-August; between 3.5°C and 7.5°C), spring (March-May; between 2.5°C and 6°C) and autumn (September-November; between 2.5°C and 5°C). All deviations calculated are based on the 1961-1990 period. No marked changes were recorded in the amount of precipitation in the spring or fall, while the winter months (December-February) have seen an increase in precipitation (between 0% and 30%), and the precipitation decreased in the summer (between -20% and 0%).

For the purposes of simulating the future changes in the quantity of organic matter in the soil, we prepared four scenarios, based on the interval values for each climate variable:

- Scenario A is based on the minimum increase in temperature and maximum decrease of the amount of precipitation;
- Scenario B is based on the minimum increase in temperature and maximum increase of the amount of precipitation;
- Scenario C is based on the maximum increase in temperature and maximum decrease of the amount of precipitation;
- Scenario D is based on the maximum increase in temperature and maximum increase of the amount of precipitation.

The climate data for the 21st century was linearly interpolated, so that e.g. the spring temperature according to scenario C increases by 6.0°C over one hundred years.

3 RESULTS
3 REZULTATI

3.1 The amount of C_{org} in the soil during the 1986-2012 period
3.1 Količina C_{org} v tleh v obdobju 1986 - 2012

The starting amount of C_{org} in the soil on the Brdo plot was calculated in the so-called spin-up phase, where a state of balance is achieved based on multiple-

Table 2: Average monthly temperature of air and amount of precipitation for the Brnik weather station for the 1986-2012 period

Preglednica 2: Povprečna mesečna temperatura zraka in količina padavin za vremensko postajo Brnik med v letih 1986-2012

Month	Jan Jan	Feb Feb	Mar Mar	Apr Apr	May Maj	Jun Jun	Jul Jul	Aug Avg	Sep Sep	Oct Okt	Nov Nov	Dec Dec	Year Leto
Temperature [°C] Temperatura [°C]	-1.15	0.24	4.59	9.34	14.66	17.92	19.70	19.22	14.44	9.64	4.31	-0.52	**9.37**
Rainfall [mm] Padavine [mm]	60.24	63.03	83.90	96.25	96.67	136.81	126.55	135.12	138.82	141.44	147.79	102.52	1326.24

Table 3: Changes in the amount of precipitation and air temperatures during the 21st century under different climate scenarios

Preglednica 3: Sprememba količine padavin in temperature zraka v 21. stoletju glede na različne scenarije klimatskih sprememb

Season Letni čas	Spring Pomlad		Summer Poletje		Autumn Jesen		Winter Zima	
Variable Spremenljivka	Temp. Temp.	Prec. Pad.	Temp. Temp.	Prec. Pad.	Temp. Temp.	Prec. Pad.	Temp. Temp.	Prec. Pad.
Scenario A Scenarij A	+ 2.5°C	+ 0%	+ 3.5°C	- 20%	+ 2.5°C	+ 0%	+ 3.5°C	± 0%
Scenario B Scenarij B	+ 2.5°C	+ 0%	+ 3.5°C	± 0%	+ 2.5°C	+ 0%	+ 3.5°C	+ 30%
Scenario C Scenarij C	+ 6.0°C	+ 0%	+ 8.0°C	- 20%	+ 5.0°C	+ 0%	+ 7.5°C	± 0%
Scenario D Scenarij D	+ 6.0°C	+ 0%	+ 8.0°C	± 0 %	+ 5.0°C	+ 0%	+ 7.5°C	+ 30%

year modelling of the input and decomposition of organic matter. Thus the calculated amount of C_{org} in the soil on the Brdo plot for 1986 is 89.09 ± 2.33 t C ha^{-1} (Figure 2). For the year 2003, we measured the amount of C_{org} in the soil on the Brdo plot in the course of soil analysis of intensive monitoring of the state of forests in Slovenia, and the result was 17.7 ± 3.1 t C ha^{-1} for the organic portion of the soil and 70.6 ± 15.5 t C ha^{-1} for the mineral part of the soil, totalling to 88.6 ± 18.5 t C ha^{-1}. The difference between average measured amount and the model-predicted amount of C_{org} in the soil on the Brdo plot is 6.35 t C ha^{-1}. With the model we further calculated the change in C_{org} in the soil for the Brdo plot. The combined values for litter and the soil organic matter up to a depth of 1 m are presented. Based on the results we can surmise that in 27 years (status January 1986 – December 2012) the amount of C_{org} increased from 89.09 ± 2.33 t C ha^{-1} to 95.03 ± 1.13 t C ha^{-1}, an average of 0.22 ± 0.05 t C ha^{-1} per year.

3.2 Simulation of changes in the stock of C_{org} in the soil for the 2012-2112 period under unchanged climate, and with consideration OF different climate scenarios

3.2 Simulacija spremembe zaloge C_{org} v tleh med leti 2012 – 2112 ob nespremenjeni klimi

The calculated stock of C_{org} in the soil on the Brdo plot using the Yasso07 model for 2012 is 95.03 ± 1.13 t C ha^{-1}. Figure 3 shows the changes in C_{org} content in the soil up to a depth of 1 m, considering the same temperature and same quantity of precipitation as indicated in the annual average for the period from 1 January 1986 to 31 December 2012 (Table 2). Initially, C_{org} stock in the soil decreases slightly, then rises to the highest value (97.23 t C ha^{-1} in 2046), then decreases constantly (92.44 t C ha^{-1} in 2112).

If we take into consideration the climate change scenarios for Slovenia (Table 3), we can observe, according to Yasso07 projections, that the C_{org} stock is ex-

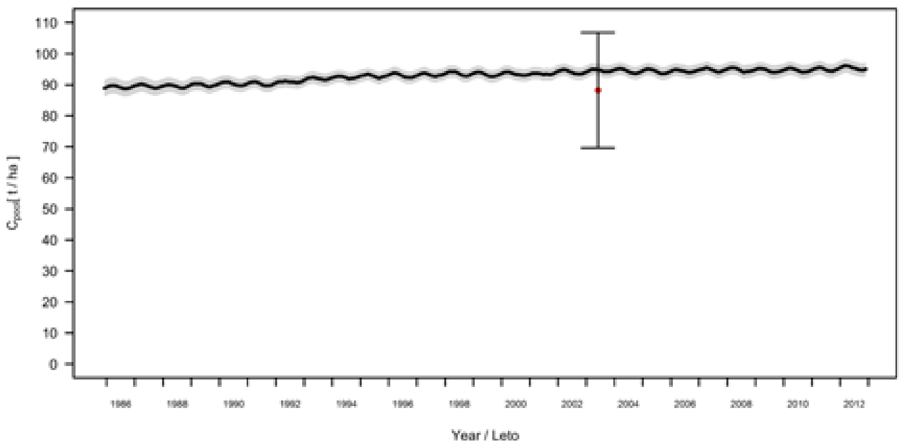

Fig. 2: Change in the stock of C_{org} in the soil during the 1986-2012 period, calculated using the Yasso07 model, taking into account the estimated input of litterfall on the Brdo plot, and based on climate data from the main meteorological station located at Brnik. The red dot marks the amount measured in the field in 2003, grey colour indicate ± 95% confidence interval.

Slika 2: Sprememba količine C_{org} v tleh v obdobju 1986-2012, izračunana z modelom Yasso07, ob upoštevanju ocenjenega vnosa odpadlega listja na ploskvi Brdo, in na podlagi podnebnih podatkov iz glavne meteorološke postaje na Brniku. Rdeča pika označuje količine, izmerjene na terenu v letu 2003, siva barva pa ± 95% interval zaupanja.

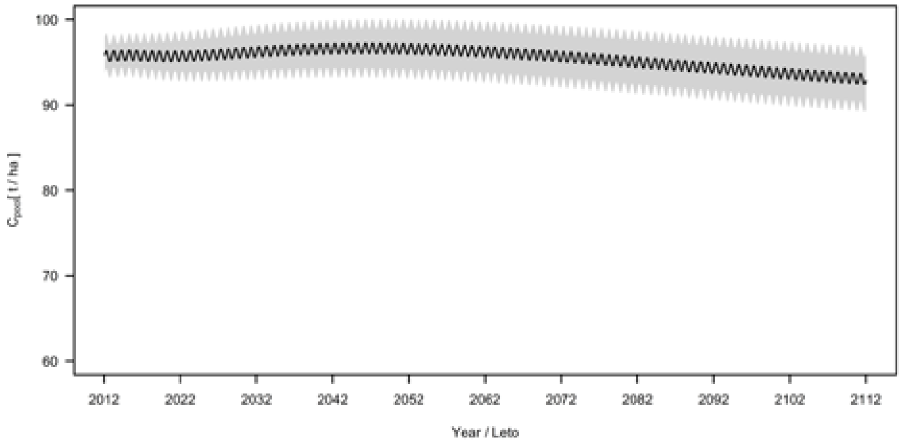

Fig. 3: Changes in C_{org} stock in the soil over time on the Brdo plot, assuming the climate remains unchanged. Grey colour indicates ± 95% confidence interval.

Slika 3: Spremembe v zalogi C_{org} v tleh v daljšem časovnem obdobju na ploskvi Brdo, ob predpostavki, da se klima ne spremeni. Siva barva označuje ± 95% interval zaupanja.

pected to decrease in the future on the Brdo plot (Figure 4). The greatest decrease can be expected in case of a change in temperature and precipitation under scenario D, which assumes maximum increase in temperature during the entire year and an increase in precipitation during wintertime, specifically from 96.08 t C ha^{-1} (highest value) to 78.63 t C ha^{-1} (lowest value). This is followed by a decrease in the stock of C_{org} in the soil, as projected under scenario C - maximum increase of temperature for the entire year and decrease in the amount of precipitation during summer months; from 95.83 t C ha^{-1} to 80.21 t C ha^{-1}. The lowest decrease in the stock of C_{org} in the soil on the Brdo plot, specifically from 96.46 t C ha^{-1} to 87.51 t C ha^{-1} over one hundred years, is projected in the event scenario A is realized, where the increase in temperatures is minimal, and in the summer precipitation is decreased by 20%. The changes are negligible from the ecological standpoint.

In addition to the decreasing trend of C_{org} stock in the soil, Figure 3 also shows the annual dynamics of the increases and decreases in C_{org}, which mainly follows the annual temperature dynamics and the input of fresh litter into the soil. The average difference between the highest and lowest stock of C_{org} within the span of a year under scenario B is 1.16 t C ha^{-1}, and is the highest of all scenarios. Here an even input of plant litter into the soil is assumed.

3.3 Change in the stock of awenh components in the soil under different climate scenarios

3.3 Sprememba zaloge organske snovi v tleh glede na različne scenarije klimatskih sprememb

Of the AWENH components, the overall amount of organic matter present in the soil is mostly composed of insoluble materials (N) (for 2012 = 47.63 ±

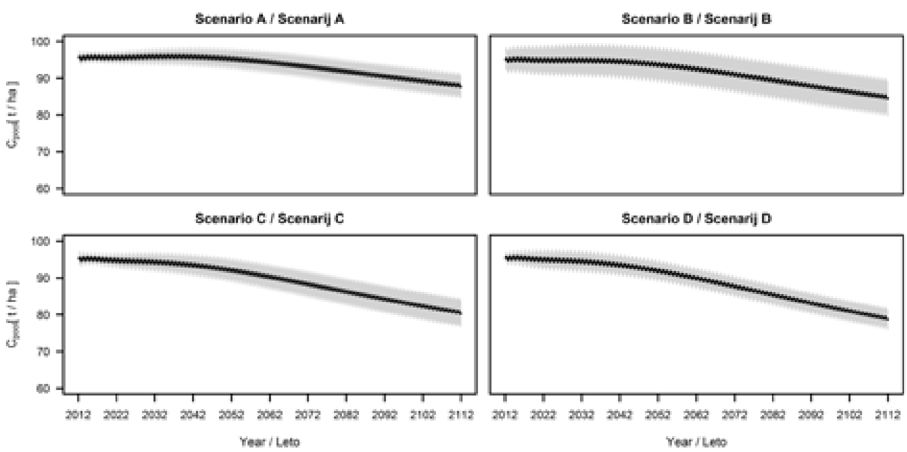

Fig. 4: Changes in C_{org} stock in the soil over time on the Brdo plot under different climate scenarios. Grey colour indicates ± 95% confidence interval.

Slika 4: Spremembe v zalogi C_{org} v tleh v daljšem časovnem obdobju na ploskvi Brdo ob različnih klimatskih scenarijih. Siva barva označuje ± 95% interval zaupanja.

1.08 t C ha^{-1}). These are not easily degradable materials, complex polyphenols, of which the prevalent one is lignin and intermediary decomposition products (lignified holocellulose, lignin-like compounds). The average coefficient of intra-year KV variation is KV = 0.292% (scenario A). These components are followed by humus (H) (for 2012 = 36.24 ± 0.55 t C ha^{-1}), which represents stable organic matter of the soil. Figure 5 shows that this component indicates the lowest annual variation of all, specifically KV = 0.006% (scenario A). Following from the quantity, which the aforementioned component takes up in the structure of the organic matter in the soil, are matters that hydrolize in acids (A) (for 2012 = 8.63 ± 0.24 t C ha^{-1}). This component is comprised mainly of cellulose and hemicelluloses. The annual fluctuations of this component are KV = 2.766% (scenario A). Following these are compounds soluble in non-polar solvents E (for 2012 = 1.39 ± 0.32 t C ha^{-1}). Average annual fluctuation of matter, which is comprised mainly of simple phenol substances and higher fatty acids, KV = 2.880% (scenario A). The lowest share is composed of water-soluble substances (W) (for 2012 = 1.15 ± 0.04 t C ha^{-1}) which, however, have the highest amount of the annual fluctuation KV = 3.650% (scenario A), as they have the fastest rate of degradation, and some of them are also directly absorbed by microorganisms. This group includes chemically fairly diverse compounds: simple sugars, amino acids, peptides and lower fatty acids.

The greatest relative decrease, hence instability, was found for the W component, specifically 28.4% under scenario A or 34.6 under scenario D. In order of the amount of change, the decrease of the component E follows: 27.2% under scenario A and 33.9% under scenario D. For compounds which hydrolize in acids A, a 22.0% decrease is projected over the next 100 years under scenario A, or 33.3% under scenario D. The amount of component N is projected to decrease by 13.4% according to the model's data (scenario A) or 25.0% (scenario D). Similarly as with the annual fluc-

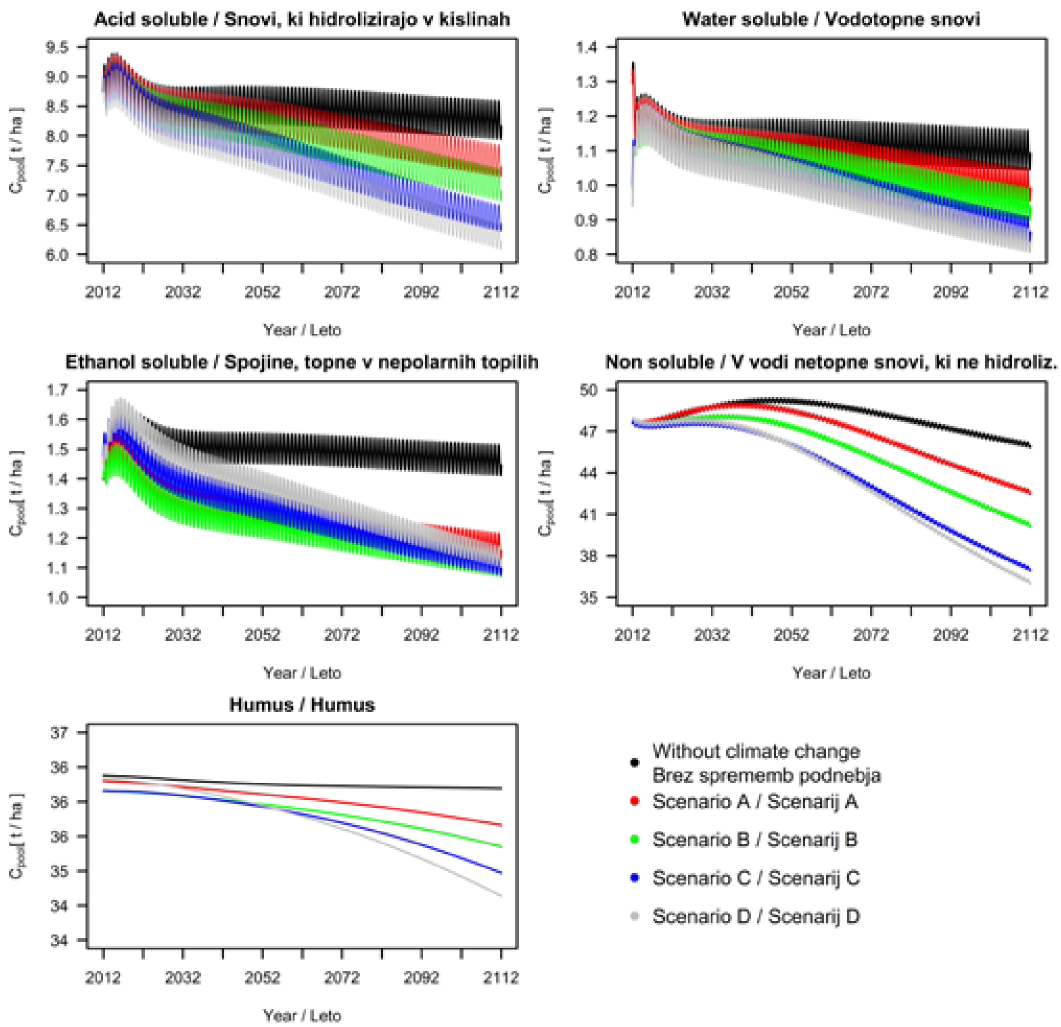

Fig. 5: Changes in the stock of AWEN components and humus in the soil over time on the Brdo plot under different climate scenarios

Slika 5: Spremembe v zalogah komponent AWEN in humusa v tleh v daljšem časovnem obdobju na ploskvi Brdo pri različnih podnebnih scenarijih tuations, humus (H) seems to be the most "resistant" in the long-term projections as well; its quantity is expected to decrease by 1.8% under scenario A, or 4.7% under scenario D.

4 DISCUSSION
4 RAZPRAVA

In the present study we used the Yasso07 model to simulate the change of organic matter in the soil, for the Brdo plot, which is included in the intensive monitoring network of Slovenian forests. We analyzed the match rate between the model values and the measured carbon content in the forest soil, and projected the changes in organic carbon under expected climate changes. We further researched the background of the model operation by evaluating the changes in individual components of organic matter (groups of chemical compounds), which the Yasso07 model uses as the object of the calculations.

The decomposition of litterfall is an important link in the biogeochemical cycle of nutrients in the forest ecosystem. Providing we do not take into account the role of mycorrhizal fungi, the nutrients bound in the organic matter have to be mineralized in order to become available to plants (VESTERDAL et al., 1995). Different compounds present in the litterfall have varying resistance to decomposition, so the decomposition of plant debris is gradual (BERG and MCCLAUGHERTY, 2003; SCHULZE et al., 2005). The first group to decompose or be used up are simple sugars, amino acids, lower fatty acids, i.e. water-soluble substances. In the interim phases, mainly higher fatty acids, cellulose and hemicellulose are subject to decomposition. Over the course of the decomposition process, the share of lignin increases, which is rather resistant to decomposition due to its complexity and diversity. The decomposition rate decreases over time due to the lack of easily degradable substances and the production of new, complex substances, which comprise humus. The nitrogen share also increases, however it is not available to plants, and it has a negative effect on decomposition, as it is crucial in the formation of degradation-resistant substances (BERG and MCCLAUGHERTY, 2003).

In the forest ecosystem, dead organic matter is produced each year, and it also decomposes. Forests are ecosystems in which the trophic chain of dead biomass is markedly prevalent (CHAPIN et al., 2011). The biomass of trees has poor nutritional value for the consumers (animals), therefore almost all plant biomass, which we do not remove from the forest as lumber, will sooner or later (except in the event of a wildfire) reach the soil in the form of plant litterfall, where it will decompose and mineralize. When the amount of newly-produced organic matter is equal to the amount of decomposed dead organic matter, we refer to it as a stable amount of organic matter (FISCHER et al., 2000). When the amount of new litterfall exceeds the amount of litterfall, which can decompose, the organic matter, especially its decomposition-resistant component, i.e. humus, begins to accumulate. Research shows that the amount of soil organic matter in forest ecosystems, given that proper management procedures are applied and in the absence of major environmental changes, increases asymptotically until a major interruption event occurs (intensive felling, wildfire, major gradation of disease or pests etc.), which significantly decreases the content of soil organic matter due to accelerated decomposition and reduced input of fresh litterfall (LAL, 2005). On the European scale it has been estimated that, on average, the carbon content in the soil increases by 22 g C /m2 per year, which is 29±15% of the production of forest ecosystems (LUYSSAERT et al., 2010).

The decomposition of organic matter and release of nutrients from organic matter is influenced by a multitude of ecologic factors, such as soil characteristics (PERALA et al., 1982; RAULUND et al., 1995), structure of litterfall, especially complexity of compounds (connected to vegetation), nutrient content (STAAF and BERG, 1982; BOCKHEIM et al., 1991), C/N ratio (ABER et al., 1982), presence of interference in the ecosystem (FISCHER et al., 2000), and presence of pollutants. The greatest impact by far is that of the climate factors (CHAPIN et al., 2011), especially soil temperature and amount of precipitation, which affects soil humidity. The correlation between soil temperature and decomposition, more specifically the respiration of microorganisms, is exponential, while there is an optimum range for soil humidity since decomposition is limited in dry and wet conditions (lack of oxygen) (BERG in MCCLAUGHERTY, 2003). Roughly, the effect of temperature is more dominant (DAVIDSON and JANSSENS, 2006), since forests generally do not thrive in very dry or constantly wet environments. In our situations we also found that the decrease of organic matter in the soil would be greater if the temperature changes than in the event that the quantity and/or distribution of precipitation changes. We can see that by comparing scenarios A and B, and scenarios A and C. It is also noticeable that the decrease in soil carbon under scenario B is greater than that under scenario A, which indicates that the total amount of precipitation is more significant in our case for the estimation of decomposition than the annual distribution. The reason can be the rather humid climate on the Brdo plot, where even in the summer the drought is not sufficiently pronounced to hinder decomposition significantly.

Like all models, Yasso07 can only offer a more or less accurate estimate of change. The determination of the uncertainty of model calculations is a requirement for conducting simulations, as high levels of uncertainty decrease the model's usefulness, or may even render it useless in extreme cases. Three partial uncertainties were already presented in the introduction (uncertainty regarding model parameters, uncertainty regarding starting circumstances, uncertainty regarding litterfall input). If we simulate the effects of climate changes, we must also take into consideration the uncertainty surrounding the projections of these changes. Besides having minimal model uncertainty, it is also important to use accurate calculations, i.e. that they correspond to actual, measurable values. The results of the Yasso07 model were compared using two methods, which differ according to their relevance. TUOMI et al. (2009) compared the calculations against the measurements of decomposition in litterbags; based on 70,000 bags of litterfall taken from 10,000 sampling points at 97 locations across Europe and North and Central America, they confirmed a good match between the decomposition measurements and the model calculations, allowing them to determine the climate conditions in which the model applies (average annual temperatures from -9.8°C to 26°C and precipitation amounts between 209 mm to 3,914 mm). It is more relevant to compare model calculations and measurements of change in total carbon content in the soil, rather than litterbags. In this regard, RANTAKARI et al. (2012) compared Yasso07 calculations with the measured 20-year changes in the amount of soil C and found that the model calculations fall within the uncertainty of the measured values.

A good measure of caution should be applied when interpreting the results presented in this study. In addition to the aforementioned uncertainties, we should also point out some of the other model weaknesses, or approximate values of the input parameters. It is crucial to have as accurate data as possible regarding the input of organic matter into the soil; even small differences simulated over decades can produce large projected losses or accumulation of C in the soil. We should point out the model's great sensitivity to the data concerning the thickness of woody debris. We also did not consider greater changes in husbandry of the observed forest. A large felling would decrease the amount of litterfall and change the environmental conditions for decomposition. The Yasso 07 model is basically simple and does not include complex ecological processes, nor the regulatory roles of the common mycorrhizal mycelial networks in forest soils (EKBLAD et al., 2013). Therefore it also does not include feedback loops. Accumulation / loss of humus, for example, can affect the productivity of the forest ecosystem and the quantity and chemical structure of the litterfall. A higher quantity of humus increases soil fertility, decreases nutrient leaching and drought effects. Furthermore, indirect effects of weather conditions are also known; in the event of less precipitation during the summer months, primary production and input of litterfall is also decreased. Including the correlation between weather conditions and primary production, consequently the quantity of litterfall is one of the key points for improvement in the future; while feedback loops are less important in conditions of sustainable management, where there are no major interferences and there is less variability in terms of the inputs and environmental conditions in the stand.

Due to the great financial and organizational requirements of regular monitoring, which might be used to determine the changes in soil organic matter or carbon in suitable time intervals, modelling of a change (also using the Yasso07 model) is a promising alternative which some European countries have already started to use (Switzerland, Finland, Norway) (RANTAKARI et al., 2012). For determining the changes of organic C in the soil on the level of larger area units (forest landscape, region), only simple models can be used, as they do not require a great number of input data, and environmental factors can be determined based on easily measurable parameters (average temperature, amount of precipitation, average soil depth, stock information about the tree biomass). Yasso07 is a model suitable for such spatial levels, and it can also be applied on the research plot level, especially if we want to test the operation of the model, or calibrate it.

5 POVZETEK
5 SUMMARY

Gozdovi, ki prekrivajo 61,1 % ± 0,7 % površine celotne Slovenije, lahko delujejo kot pomemben vir ali ponor organskega ogljika (C_{org}). Pomen gozdov kot skladišča (ponora) organskega ogljika je priznan / prepoznan v Okvirni konvenciji Združenih narodov o spremembi podnebja ter v Kjotskem protokolu. Gozdna tla

se kot zbiralnik C_{org} v nacionalnih poročilih pojavijo v poglavju o zalogah C_{org} v opadu in poglavju o zalogah C_{org} mineralnem delu tal. Kljub pomenu oz. vlogi, ki jo imajo gozdna tla za vezavo ogljika in zato tudi v samem Kjotskem protokolu, pa ni na voljo enotne metodologije spremljanja sprememb nežive organske snovi, kamor po definicijah kjotskega protokola spadata tudi opad in organska snov v gozdnih tleh. Tudi v nacionalnih popisih gozdov sprememb ogljika v gozdnih tleh navadno ne merimo. Dodatna težava pri vrednotenju sprememb količine C_{org} v gozdnih tleh je prostorska variabilnost gozdnih rastišč, saj so pričakovane časovne spremembe manjše od prostorske variabilnosti zaloge C_{org} v gozdovih. Alternativna rešitev so modelski izračuni, ki se pogosto uporabljajo za oceno zaloge C_{org} v gozdnih tleh in njihove spremembe. Modeli se med seboj razlikujejo v kompleksnosti in po potrebni količini vhodnih podatkov. Tako veljata Yasso07 in RothC za razmeroma preprosta modela, medtem ko je npr. ROMUL bolj zapleten model kroženja C_{org} v gozdnih tleh z večjim številom zahtevanih vhodnih podatkov. Namen prispevka je na ploskvi ''Brdo'', ki je vključena v mrežo intenzivnega spremljanja stanja gozdov v Sloveniji od leta 2003, poskusno uporabiti model Yasso07 in primerjati ocene sprememb količine organske snovi v tleh glede na različne spremembe temperature zraka ter količine padavin v prihodnosti.

Ploskev Brdo je ena od desetih ploskev intenzivnega spremljanja stanja gozdov v Sloveniji. Osnovana je bila leta 2003 na površini 1 ha. Matična podlaga je prodni zasip, tla so distrična rjava. Ploskev obsega drugotni kisloljubni gozd rdečega bora (*Pinus sylvestris*) z borovnico (*Vaccinio myrtilli - Pinetum*).

Model Yasso07 opisuje razgradnjo organske snovi v gozdnih tleh. Model Yasso07 temelji na treh predpostavkah razgradnje organske snovi, in sicer: i) rastlinski opad sestavljajo različne komponente, ki se razlikujejo v hitrosti razgradnje; ii) hitrost razgradnje posamezne skupine spojin je odvisna od klimatskih razmer, ki jih lahko poenostavljeno opišemo s podatki o temperaturi zraka in podatki o padavinah, ter iii) procesi razgradnje posameznih skupin spojin povzročijo pretvorbe določenega deleža posamezne AWEN-komponente v drugo komponento ter izgubo organskega ogljika iz talnega sistema v obliki CO_2. Iz manjšega dela AWEN-komponent nastaja proti razgradnji razmeroma odporen humus (H). Skupno je v modelu Yasso07 vključenih 25 različnih parametrov, ki so bili ugotovljeni empirično na podlagi velikega števila vzorcev (opadnih vrečk) iz Evrope in Severne Amerike.

Model deluje tako, da najprej vse vnose organske snovi v tla (listi, veje, panji, drobne in debele korenine) razdeli na količino posamezne AWEN-komponente ter le-to prišteje trenutni količini iste komponente, ki je že v tleh. Nato iz dobljene vsote ob poznavanju hitrosti razgradnje posamezne komponente predvidi ostanek te komponente po določenem času ter količino, ki se v tem času pretvori bodisi v drugo AWEN-komponento ali humus. Parametri hitrosti razgradnje niso fiksni, pač pa so odvisni od temperature in vlažnosti, pri olesenelih delih tudi od velikosti (premera) tega dela. Rezultat modela Yasso07 je skupna količina organskega ogljika do globine 1 m, vključno z ogljikom v odmrlem lesu, v organskih podhorizontih Ol, Of in Oh ter organski snovi v mineralnem delu tal. Model lahko poda tudi spremembo količine organskega ogljika ali emisijo CO_2 iz preučevanih tal. Yasso07 je uporaben tudi za simulacijo sprememb podnebja (večja temperatura, manjša količina padavin, spremenjena medletna porazdelitev padavin) ali sprememb rabe tal (krčitve, zaraščanje).

Za zagon modela Yasso07 potrebujemo podatke o količini opada in njegovi kakovosti (razmerjih med skupinami prej omenjenih skupin), podatke o temperaturi in padavinah ter podatke o začetki količini C_{org} v tleh. Predpostavili smo, da lahko na ploskvi Brdo organska snov prihaja v tla iz šestih različnih virov: a) nadzemni nelesni opad, npr. odpadlo listje oz. odpadle iglice; b) nadzemni lesni opad manjših dimenzij, npr. veje in vejice; c) nadzemni lesni opad večjih dimenzij, npr. debla podrtih dreves; č) podzemni nelesni opad, npr. drobne korenine; d) podzemni lesni opad manjših dimenzij, npr. korenine; e) podzemni lesni opad večjih dimenzij, npr. panji. Ker za ploskev Brdo natančnih podatkov o količini opada posameznega vira nimamo, smo le-te prevzeli iz literature oz. smo jih izračunali podobno kot v primerljivih poročilih. Nato smo iz literaturnih podatkov prevzeli delež posameznega dela drevesa, ki vsako leto odmre oz. ponazarja vnos organske snovi v tla. Za lesni opad je v model Yasso07 treba podati tudi povprečno velikost opada, in sicer kot premer.

Za zagon model Yasso07 potrebuje podatke o povprečni mesečni oz. letni temperaturi zraka, povprečni amplitudi temperature (povprečna polovica razlike med najtoplejšim in najhladnejšim mesecem v letu) ter povprečni mesečni oz. letni količini padavin. Klimatske podatke smo pridobili iz spletne strani ARSO (http://meteo.arso.gov.si). Povprečna letna količina padavin znaša 1326,2 mm, povprečna letna temperatura je 9,4 °C, povprečna letna amplituda temperature pa 11,3 °C. Spremembe količine padavin in temperature zraka v 21. stoletju smo povzeli po projekcijah sprememb količine padavin ter povprečne temperature zraka, ki jih je za slovenijo izdelal Bergant (2003). Izračuni Berganta kažejo predvsem izrazitejši dvig temperature zraka v topli polovici leta v primerjavi s hladno polovico ter zmanjšanje količine padavin v topli polovici leta in porast količine padavin v hladni polovici leta. Za simulacijo sprememb količine organske snovi v tleh v prihodnosti smo oblikovali štiri scenarije, na podlagi intervalnih vrednosti za posamezno podnebno spremenljivko: a) scenarij A temelji na minimalnem dvigu temperature ter maksimalnem zmanjšanju količine padavin; b) scenarij B temelji na minimalnem dvigu temperature ter maksimalnem povečanju količine padavin; c) scenarij C temelji na maksimalnem dvigu temperature ter maksimalnem zmanjšanju količine padavin; d) scenarij D temelji na maksimalnem dvigih temperature ter maksimalnem povečanju količine padavin.

Začetno količino C_{org} v tleh na ploskvi Brdo smo izračunali na podlagi večletnega modeliranja vnosa in razgradnje organske snovi, da se doseže ravnovesno stanje. Tako izračunana količina C_{org} v tleh na ploskvi Brdo za leto 1986 znaša 89.09 ± 2.33 t C ha^{-1}. Za leto 2003 smo količino C_{org} v tleh na ploskvi Brdo izmerili v sklopu pedoloških preučevanj intenzivnega spremljanja stanja gozdov v Sloveniji in znaša 88.6 ± 18.5 t C ha^{-1}. Razlika med izmerjeno in z modelom napovedano količino C_{org} v tleh na ploskvi Brdo znaša 6.35 t C ha^{-1}. Na podlagi rezultatov modela sklepamo, da je v 27 letih (stanje januar 1986 – december 2012) količina C_{org} narasla z 89.09 ± 2.33 t C ha^{-1} na 95.03 ± 1.13 t C ha^{-1}, povprečno 0.22 ± 0.05 t C ha^{-1} letno. Izračunana zaloga C_{org} v tleh z uporabo modela Yasso07 za leto 2012 znaša 95.03 ± 1.13 t C ha^{-1}. Simulacija sprememb zaloge C_{org} v tleh za obdobje 2012-2112 ob nespremenjenem podnebju kaže, da zaloga C_{org} v tleh najprej rahlo pade, potem naraste na največjo vrednost (97.23 t C ha^{-1} leta 2046) in nato konstantno upada (92.44 t C ha^{-1} leta 2112). Če upoštevamo scenarije podnebnih sprememb za Slovenijo, lahko glede na napovedi modela Yasso07 opazimo, da se bo zaloga C_{org} v tleh na ploskvi Brdo v prihodnosti zmanjševala. Največje zmanjšanje je pričakovati v primeru spremembe temperature in količine padavin po scenariju D, ki predvideva maksimalno povečanje temperature v celotnem letu ter povečanje količine padavin v zimskem času, in sicer s 96.08 t C ha^{-1} (najvišja vrednost) na 78.63 t C ha^{-1} (najnižja vrednost). Najmanjše zmanjšanje zaloge C_{org} v tleh na ploskvi Brdo, in sicer s 96.46 tC/ha na 87.51 t C ha^{-1} v stotih letih, je predvideno v primeru uresničitve napovedi scenarija A.

Razgradnja opada je pomemben člen v biogeokemičnem kroženju hranil v gozdnem ekosistemu. Dokler se hranila, vezana v organsko snov, ne mineralizirajo, ne postanejo ponovno dostopna rastlinam. Različne spojine v opadu so različno odporne proti razgradnji, zato razgradnja rastlinskih ostankov poteka postopoma. Najprej se razgradijo ali celo enostavno porabijo preprosti sladkorji, aminokisline, nižje maščobne kisline, torej snovi, ki so topne v vodi. V srednjih fazah razgradnje se razgrajujejo predvsem višje maščobne kisline, celuloza in hemiceluloze. Med razgradnjo narašča delež lignina, ki je zaradi svoje kompleksnosti in raznovrstnosti precej odporen proti razgradnji. Hitrost razgradnje s časom upada zaradi pomanjkanja lažje razgradljivih snovi ter tvorbe novih kompleksnejših snovi, ki tvorijo humus.

Zaradi velikih finančnih in organizacijskih zahtev rednega monitoringa, ki bi v ustreznih časovnih zaporedjih lahko ugotavljal spremembo talne organske snovi oz. ogljika, je modeliranje sprememb (tudi z modelom Yasso07) obetajoča alternativa, ki jo v svojih letnih poročilih že uporabljajo nekatere evropske države (Švica, Finska, Norveška). Za ugotavljanje sprememb organskega C v tleh na ravni večjih prostorskih enot (npr. rastiščno gojitveni razredi, gozdna krajina, regije) so lahko uporabni le preprostejši modeli, ki ne zahtevajo velikega števila vhodnih podatkov in pri katerih so dejavniki okolja lahko merljivi parametri (povprečne temperature, količina padavin, povprečna globina tal, inventurni podatki o drevesni biomasi). Yasso07 je model, primeren za takšne prostorske ravni, uporaben pa je lahko tudi na ravni raziskovalne ploskve, posebej če želimo preveriti delovanje modela oz. ga kalibrirati.

6 ZAHVALA

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