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CARBON STOCK IN AN EVEN-AGED NORWAY SPRUCE STAND ON THE ORIGINAL BEECH SITE AND ITS CHANGES DURING CLEAR-CUTTING REGENERATION

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Abstract

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The paper summarizes the results of a long-term monitoring the development of a spruce monoculture established at the beginning of the 20th century on the original beech site in the region of the Drahanská vysočina upland (the Rájec project). The results are presented from the aspect of changes in the accumulation and transport processes of carbon. The whole process of changes is characterized in particular stages of the forest stand development on the studied area: (1) the conversion of original beech stand for spruce monoculture, (2) the first stage after the clear-cutting regeneration of spruce, (3) the second stage of the clearing development, (4) the stage of the spruce stand development of the 2nd generation after cleaning and leaving the stand development without silvicultural interventions. Significant changes in carbon accumulation occurred through the conversion of the species composition of the original beech stand to a spruce monoculture, deceleration of decomposition processes and accumulation of carbon in surface humus. As well the development of herb vegetation on the clear-cut area shows great importance for the biogenic elements cycle and carbon, which begins in the third year after felling.

Key words: spruce monoculture, clear-cutting regeneration, carbon

Introduction

As compared with the present distribution of spruce in the ČR, its original natural range was much smaller. Its upper limit was in the Krkonoše Mts at an altitude of 1200–1350 m, in the Šumava Mts (Bohemian Forest) 1400 m, in the Krušné hory Mts (Ore Mts) 1200 m and in the Hrubý Jeseník Mts 1350 m (Mráček, Pařez, 1986).

Of course, it occurred also at lower locations in mixtures with silver fir and beech. In addition, spruce penetrated from higher altitudinal zones to lower zones, namely first at northern slopes and to moist and cold basins and valleys (Nožička, 1972).

The establishment of pure spruce stands was mostly brought about by economic requirements associated with the increasing consumption of wood (mines, building industry) and, on the other hand, also by the reconstruction of devastated areas. In addition to positive effects of establishing spruce monocultures (production of wood), negative consequences were often discussed, particularly effects on soil and the extent of damage caused by biotic and abiotic factors.

The aim of our paper is to assess effects of the changed species composition of beech to spruce and consequences of the clear-cut regeneration of a spruce monoculture in its particular stages on the fixation, accumulation and transport processes of carbon.

According to Paschalis-Jakubovicz (2004), the value of carbon in the wood biomass in Czech forests amounts to more than 200 million tons. According to the database of the Institute of Forest Management Planning in the CR (Henžlík – personal communication) this value ranges from 300 to 400 million t carbon. Thus, accumulation of carbon in the wood biomass of Norway spruce in the CR amounted to about 180 million tons.

Forest ecosystems are typical of their multifunction character (production, soil and water protection, recreation, biodiversity and carbon sequestration). Nevertheless, the fulfilment of some functions can negatively affect other functions. For example, to aim management at the accumulation of wood biomass, which also positive affects values of carbon fixation and accumulation, can decrease biodiversity (Warran, Patwardhan, 2009). It means that to replace diversity ecosystems by one-species plantations can induce higher accumulation of carbon but can also cause lower biodiversity.

Main pools of the carbon stock in forests are:

– plant communities (trees, shrubs, herbs)
– forest floor
– forest soils
– dead trees and shrubs lying on the soil surface.

The terrestrial sequestration of carbon is a process when CO_2 from atmosphere is absorbed by vegetation and accumulated in particular ecosystem components as mentioned above. At the same time, the process of carbon release to atmosphere occurs (biomass and soil respiration).

Carbon sequestration with close dependence at the level of production is modified by the woody species, regional climate and methods of management. For example, pine plantations at south-east of the USA can accumulate 250 t carbon per 1 ha per 90 years or about 2.5 t. $ha^{-1}.year^{-1}$ (Birdsey 1996 in "Carbon Sequestration in Agriculture and Forestry", U.S. Environmental Protection Agency).

Soil is the most stable environment for carbon although even there, some factors can affect negatively, such as intensive soil preparation for the regeneration of forest stands or erosion when the upper organo-mineral horizon is often washed away.

Table 1. Values of carbon accumulation in vegetation and soil are different according to climatic zones. Lal et al. (1997) give for:

	Carbon pools (mg . ha^{-1})		
Ecosystem	Vegetation	Soil	Total
Temperate evergreen forest	160.1	134.0	294.1
Temperate deciduous forest	130.5	132.9	264.4
Boreal forest	89.7	205.8	295.5
Tropical evergreen forest	186.9	113.3	298.3

Comparing data mentioned above we can state that in forest ecosystems, the ratio between carbon accumulation in vegetation and soil is rather balanced as compared with boreal and tropical forests whereas in boreal forests, the highest accumulation is in the surface humus and mineral soil; in tropical forests, on the contrary, in vegetation.

Wood after felling retains carbon in products with long-term use (construction of houses etc.) whereas wood used, eg, for the production of paper or wood used for heating finishes generally the carbon cycle.

Values of carbon fixation and accumulation have to be based on data of the forest stand inventory including the annual and mean annual increment. Nevertheless, data obtained by detailed studies are also necessary. It refers particularly to the flow of carbon at long-term research field stations. Thus, we could use this complete information from the study of primary production of trees (Vyskot, 1981; Palát et al., 1992) and herbs (Vašíček, Klimo, 1987; Vašíček, Viewegh, 1992) and from the study of element cycle (Klimo, 1992) and water cycling (Prax, 1992) at the Rájec long-term research station in the Drahanská vrchovina upland.

Description of the locality

The Rájec long-term experiment station is situated in a geographical complex of the Drahanská vrchovina upland.

It is located on the eastern slope of the watershed ridge oriented in the N-S direction. The slope can be interpreted as a cryoplanatic terrace with weathered fragments of granodiorite scattered by frost.

The original forest stand: *Fagus sylvatica*
Actual forest stand: *Picea abies* K a r s t. 1st generation (80 years)
Soil type: Acid Cambisol
Mean annual precipitation: 638 mm
Mean annual temperature: 6.3 °C
Altitude: 625 m (590–640 m)

From the aspect of the history of forest stands at the Rájec field research station, it is possible to note that the original beech stand was devastated by fire and wind being cut down in the course of the 19th century and replaced by the present spruce monoculture at the turn of the 19th and 20th centuries. This change was also affected by the increased need of beech for the production of charcoal for developing industrial production.

Fig. 1. The stand of Norway spruce.

Methods

1. For the calculation of carbon sequestration and accumulation in the biomass of a tree and herb layer there was a relationship to data on the primary production (Vyskot, 1981; Vašíček, Viewegh, 1992; Palát et al., 1992), the weight of carbon being calculated according to Divigneaud (1988).
2. The forest floor layers was marked: L – litter layer, F – fermentation layer, H – humus layer, A – organomineral soil horizon.
3. Total carbon: modification of the Tjurin's method; evaporated sample is oxidized using chromosulfuric acid at 124 °C; after oxidation, the surplus chromosulfuric acid is determined.
4. To intercept lysimetric waters under particular soil horizons, a lysimeter of Shilovova type (1955) was used.
5. The determination of carbon in an organic horizon and in precipitation and soil waters was carried out for C in an analyzer LECO TruSpec CN at the temperature combustion 950/850 °C.
6. The surface humus weight in a mature stand was determined by sampling on plots of 0.5 m^2 with fivefold repetition and the forest floor weight on a clear-felled area after cutting with 21 repetitions.
7. The statistical processing of analytical data was carried out in BASIC using an ADT computer. Methods of testing (t-test, pair test) were applied.
8. Carbon respiration from soil was calculated according to Grunda, Kulhavý, 1992.

Results and discussion

1. Changes in the stand species composition (beech stand – Norway spruce monoculture)

As already mentioned in Introduction, until 1900, a beech stand occurred on the studied area although rather devastated in the last period. Changes in the stand species composition became markedly evident also in the accumulation of carbon in particular parts of the ecosystem. The most distinct changes were noted in the accumulation of carbon in forest floor.

The litter layer (forest floor) shows the highest accumulation in a original beech stand in F layer, viz. 6000 kg. In L layer 5000 kg.ha^{-1} whereas H layer is either missing or shows minimum accumulation of carbon, namely about 250 kg.ha^{-1}. In a spruce monoculture, the highest accumulation of carbon occurs in H layer, viz. 11 000 kg.ha^{-1} and L and F layers do not markedly differ from layers in the beech stand. It means that through the change of the species composition of stands the carbon stock in forest floor increased from about 11 to about 25 t.ha^{-1} in a beech stand within a period of 80 years.

T a b l e 2. To compare carbon accumulation in the biomass of beech and in soil, we used data from a similar site (Solling) (Reichle, 1981):

	Solling – beech	Rájec – spruce
Aboveground biomass	79 382 kg.ha^{-1}	142 200 kg.ha^{-1}
Roots	11 040 kg.ha^{-1}	24 500 kg.ha^{-1}
Forest floor	19 500 kg.ha^{-1}	25 000 kg.ha^{-1}
Soil-root zone	106 000 kg.ha^{-1}	85 000 kg.ha^{-1}

Comparing the total accumulation of carbon in the ecosystem of beech and spruce, the total carbon reserve is higher in the spruce stand (277 000 kg.ha^{-1}) as against beech (215 922 kg.ha^{-1}). The higher accumulation in the spruce stand is conditioned particularly by the higher accumulation in the biomass of trees and surface humus. In the beech stand, higher accumulation occurs in mineral soil of the root zone. This carbon represents considerably stable accumulation of C.

Weishampel et al. (2009) noted significant differences between broadleaved and coniferous stands in the area of Minnesota (USA). The total accumulation of MgC per 1 ha in broadleaved forests was characterized by a value of 153 and in coniferous forests by 197 MgC per ha. A marked difference was noted particularly at forest floor.

Also Cannel (1996) concludes that fast-growing species accumulate carbon faster than slow-growing species although, from the aspect long-term accumulation of carbon, slow-growing species are preferred.

T a b l e 3. Carbon stock in the biomass of spruce monoculture (80 years) forest floor and in the soil (kg DM. ha^{-1}) – Rájec project.

Component	**C kg.ha^{-1}**
Needles	11 900
Shoots	5 300
Branches	10 000
Stems	115 000
Total aboveground	**142 200**
Roots	24 500
Total in biomass	**166 700**
Forest floor	25 000
Mineral soil of rooting zone	85 000
Total C-stock in ecosystem	**276 700**

T a b l e 4. Carbon stock on the ecosystem level calculated from long-term Solling case study (Reichle, 1981) – kg.ha^{-1} DM.

Component	C stock age 87 y	C stock age 34 y	Locality
Needles	8 940	9 435	**Solling Project, Site F1, Germany F3**
Branches	14 105	9 365	*Investigator*: Ulrich, Ellenberg
Stems	99 200	52 550	*Forest type*: Spruce plantation (*Picea abies*)
Total aboveground	112 245	71 350	*Geology*: Buntsandstein
Roots	35 860	17 280	*Soil type:* Brown forest soil (acid)
Total in biomass	158 105	88 630	*Stand age:* 87 y (F1), 34 y (F3)
Forest floor	24 500	26 000	*Annual precipitation:* 1063 mm
Mineral soil of rooting zone	95 000	95 000	*Mean annual temperature*: 5.9 °C
Total C-stock in ecosystem	277 605	209 630	*Altitude*: 505 m

The proportion of spruce creates about 55% in forests of the Czech Republic. Thus, from the aspect of carbon fixing and accumulation, spruce shows considerable importance. Therefore, we focussed on the distribution of carbon reserves in particular components of biomass.

Data in Tables 3, 4 show that the highest accumulation of carbon in a spruce monoculture account for the tree stems and mineral soil in the root zone. Accumulation of carbon in forest floor, which accumulates rather quickly contrary to mineral soil, is also important. Comparing two spruce stands from the Solling project (aged 87 and 34 years) we can see that the accumulation of organic matter takes place evidently rather quickly after the establishment of a spruce monoculture, namely within about 40 years and then its accumulation slows (Table 4). Comparing carbon accumulation at particular components of a mature stand from Rájec and Sollingen, there are no significant differences (Tables 3, 4). Accumulation of carbon in needles of a 34-year old stand is rather marked, which can be conditioned both by the density of trees in a stand and by the crown condition.

To know the carbon cycle in the forest ecosystem, data on the transport of carbon are important (Table 5). Carbon input on the soil surface is created by litter and by the carbon content in precipitation.

T a b l e 5. Transport of carbon by litterfall precipitation and soil water percolation through a Norway spruce ecosystem (kg.ha^{-1}.year^{-1}) – period 1977–1980.

Component		C kg.ha^{-1}.y^{-1}
Literfall	stand	2 500
	roots	600
In water	input into stand	19.6
	input to soil surface by canopy drip by stem flow	 46.2 4.2
	output from L layer	160.0
	output from F layer	175.0
	output from H layer	150.0
	output from A layer	35.0

Fig. 2. The first stage after clear-cutting.

The value of dissolved organic carbon (DOC) transport from the surface humus to mineral soil is important. Table 5 shows that the highest accumulation of carbon occurs in horizon A where there is also the highest "litter" of roots, the horizon being relatively shallow and, therefore, carbon accumulation does not occur in deeper soil layers as in beech stands.

Total respiration from soil in the studied ecosystem is 11.5 t CO_2 per 1 ha, which represents 3100 $kg.ha^{-1}.y^{-1}$ (Grunda, Kulhavý, 1992). Of this quantity, about 30–40% of the produced CO_2 is derived from the respiration of roots.

2. Changes under influence of clearcutting regeneration

In 1977, the spruce monoculture regeneration was carried out using a clear-felling system. In the first stage of clear felling, following changes of carbon stock were noted:
Using the technology of whole-tree logging the significant output of carbon was noted:
142 200 $kg.ha^{-1}$.
This amount can be decreased by about 10% carbon included in needles and shoots, which fell off in the course of felling operations on the soil surface, i.e.:
1 200 $kg.ha^{-1}$ needles
530 $kg.ha^{-1}$ shoots
Total 1 730 $kg.ha^{-1}$,

Fig. 3. The second stage of clear-cutting with maximum of herb vegetation.

that means that the total output caused by felling was about 140 500 kg.ha^{-1}.

Considerable amounts of carbon remained accumulated in the surface humus layer. Due to logging operations, however, marked destruction of the surface humus natural stratification occurred, which could be characterized by 3 situations:

– areas where carbon accumulation increased to about 41 500 kg.ha^{-1}
– areas with the accumulation of carbon 36 400 kg.ha^{-1}
– areas on skidding tracks where minimum stock occurred, viz. about 640 kg.ha^{-1}.

Thus, the average value of carbon accumulation on the soil surface in the first stage of clear felling increased as against the original spruce stand because the extraction track area occupied only a relatively small area. Due to felling and skidding operations on a clear-cut area the variability of carbon distribution increased from 19 to 49%.

When we compare carbon concentration in water under an organic horizon (L+F+H) in a 80-year spruce stand and on a clear-cut area, there is no marked difference: 32.1 mg.l^{-1} in the 80-year stand and 30.8 mg.l^{-1} on the clear-cut area. Of course, with respect to the higher impact of precipitation on the soil surface at the clear-felled area, the absolute value of dissolved carbon percolating from H horizon to mineral soil will be higher on the clear-cut area.

In the first stage after clear-felling (1977–1980), carbon respiration from soil fluctuates about a value

13.1 t CO_2. ha^{-1}, ie. 3.57 t C ha^{-1}. y^{-1}.

3. Second stage of clear-felling area

In the second stage of clear-felling area a newly established spruce stand develops. Gradually, the growth of vegetation on a clear-felled area begins, the production of which reaches its maximum 3 to 7 years after felling (Vašíček, Viewegh, 1992). Then, its production decreases under the effect of the new Norway spruce stand canopy.

Carbon accumulates on a clear-felled area in the second stage of development

a) in a herb layer
b) in a newly planted spruce stand
c) in the layer of surface humus
d) in the organomineral layer of soil.

Carbon accumulation in the first three components changes dynamically depending on the biomass growth processes and decomposition processes in the surface humus.

Carbon accumulation in the organomineral layer is relatively stable.

a) Carbon in the herb layer
   1981 4 000 $kg.ha^{-1}$
   1984 2 350 $kg.ha^{-1}$
   1986 300 $kg.ha^{-1}$
b) Carbon in the newly planted spruce stand and in natural self-seeding (1980–1986)
   1980 24 $kg.ha^{-1}$
   1981 77 $kg.ha^{-1}$
   1982 280 $kg.ha^{-1}$
   1983 850 $kg.ha^{-1}$
   1984 1 800 $kg.ha^{-1}$
   1985 3 580 $kg.ha^{-1}$
   1986 7 200 $kg.ha^{-1}$
c) Carbon in the forest floor

The process of decomposition is significantly lower in F layer. In H layer, partial enrichment even occurs, which is the result of decomposition processes in L and F layers. Data mentioned above were obtained under conditions of removing the herb vegetation whereby the process of decomposition was accelerated.

Generally, we can note that the H layer of surface humus changes slowly passing (in little changed values) to the second spruce stand generation. With respect to the markedly increased variability in the organic horizon accumulation caused by the whole-tree technology at the stand regeneration the rate of the organic horizon decomposition was monitored on a model experiment when a plot was installed imitating the original condition in the stand before felling. A decrease was monitored on the plot in next two years.

T a b l e 6. Changes of accumulated carbon in surface humus on a clear-felled area (kg.ha^{-1}).

Layer	1979		1980		1981	
	kg.ha^{-1}	%	kg.ha^{-1}	%	kg.ha^{-1}	%
L	3 900	100	3 650	94	1 400	36
F	9 850	100	7 550	77	7 350	75
H	10 850	100	11 300	104	10 050	93
L, F, H	24 600	100	22 500	91	18 800	80

d) Carbon in the organomineral layer of soil

We start from a condition that this value is rather constant although it is affected by the input of about 150 kg C ha^{-1}.year^{-1} and part of carbon moves with percolating water. The value is about 85 000 kg.ha^{-1}. During this stage, regeneration of physical properties of soil gradually occurred, particularly of the loosing function of the herb layer root system and of the new spruce stand.

Respiration in the second stage of the clear-cut area development is dependent on the development of a newly established stand and on silvicultural measures. According to Kulhavý, Formánek (2002), it shows following values: 3.4 t C ha^{-1}.year^{-1} in a stand free of thinning and 4.7 t C ha^{-1}.year^{-1} in a stand after thinning.

In the next development of carbon accumulation after clear-felling regeneration, in addition to the increased accumulation of carbon in the biomass of the spruce forest of the second generation conditioned by increasing the increment and decreasing its accumulation in the herb layer, changes occurred due to decomposition processes of the organic horizon affected particularly by silvicultural measures.

4. The third stage of a clear-felled area

In this stage, a spruce stand of the second generation with fully closed crowns is a dominant factor. Herb vegetation totally receded. In the stand part, thinning was carried out and part of the stand was left to spontaneous development without any silvicultural interventions.

We were interested in potential effects of thinning on the accumulation of carbon in forest floor. Thinning represents reduction of the number of trees, higher input of light into crowns of trees and to the soil surface. Thus, both production and accumulation of carbon in the stand biomass can be increased as well as acceleration of the decomposition and transport of dissolved organic carbon (DOC) into mineral soil.

Novák et al. (2006) mention that in a young spruce stand aged 27–39 years, which also corresponds to our situation, the amount of litter in the first stage of monitoring (about 5–6 years) was lower in an area with thinning as compared with a control area while in the second stage of monitoring, the amount of litter was higher in an area with thinning.

After thinning, on the one hand, crowns of felled trees were evidently removed and, on the other hand, increased production of needles increased also the amount of litter. It was

T a b l e 7. Some statistic parameters of the carbon stock in the forest floor of plots with and without thinning (t.ha^{-1} of DM).

Parameters	Experimental plots							
	without thinning				after thinning			
	L	F	H	A %	L	F	H	A %
Mean values	1.97	6.36	5.50	9.36	1.88	6.52	9.25	12.36
Median	2.02	6.29	6.00	9.00	2.70	4.82	8.06	8.90
Minimum values	1.17	3.29	1.60	6.50	1.02	2.88	4.04	6.60
Maximum values	2.48	9.96	8.45	12.2	2.10	10.7	19.41	22.1
Variation coefficient	0.26	0.39	0.54	0.22	0.26	0.51	0.66	0.52

rather difficult to evaluate the condition of forest floor at 2 variants of our area. Differences between the area with thinning and the area left to its spontaneous development were markedly affected by the increased variability of forest floor caused by the removal of stems including their crowns immediately after felling. It is also proved by the high variability of the distribution of forest floor on a control plot (40%) and on the area after thinning (33%). High variability was detected particularly in H layer (54.7 and 66.3%) and the smallest variability in L layer (in both cases 26.2%), which is affected by the current process of litterfall. It indicates that the input of carbon is in principle the same in the initial stage of the stand development after thinning.

Moreover, it is necessary to stress that even after about 30 years from felling and the establishment of a new Norway spruce stand, the high accumulation of carbon remains in H layer (about 6 t C.ha^{-1} on the area without thinning and 8 t C.ha^{-1} on the area with thinning). It also proved at the conversion of spruce monocultures to beech stands (Klimo, Kulhavý, 2006).

Šimek (2003) summarizes that organic substances, which originated in the process of decomposition and resynthesis of organic matter in soil, are the largest reservoir of carbon in terrestrial ecosystems. This generalized opinion is proved, for example, by the accumulation of carbon in soils of the Chernozem type. As for the forest ecosystem comparison, this situation is balanced, for example, between spruce and beech stands. Nevertheless, in spruce stands, markedly higher accumulation of carbon occurs in forest floor where there are about two-time higher values as against beech stands. Berger et al. (2002) differentiate carbon stock in 0–50 cm mineral soil according to site conditions and mention that in spruce stands, this supply is higher on flysch.

Comparing similar spruce and beech stands in Central Europe, the total accumulation of carbon in spruce and beech stands (biomass + soil) is higher in spruce ecosystems (about 290 000 and 220 000 kg.ha^{-1} in spruce and beech ecosystems, respectively).

However, this view may not be valid generally with respect to site conditions and methods of management. In this comparison, there is unambiguously marked increase of carbon accumulation in the surface humus of spruce stands already in the first generation of spruce monocultures. The highest reserves of carbon are accumulated in H layer, which is then rather stable even in the course of the spruce stand regeneration by a clear-felling method or by transformation to beech or mixed stands.

Conclusion

1. In the Czech Republic, spruce stands show an important proportion in the sequestration and accumulation of carbon.
2. The change of beech stands to spruce monocultures at lower locations (altitude 400-600 m) brought about particularly of carbon stock in forest floor.
3. In the course of clear-felling regeneration, the marked increase occurs of the variability of accumulated carbon in the forest floor (from 19 to 49%) and the single output of carbon (about 140 500 kg.ha^{-1}) from the ecosystem.
4. Herb vegetation (maximum 2350 C kg.ha^{-1} about 5 years after felling) shows an important proportion in the sequestration of carbon on the clear-felled area in the second stage of its development.
5. The forest floor destruction by clear felling regeneration (hole-tree harvesting) remains even 30 years after regeneration and the significant effect of thinning did not occur.
6. The high accumulation of carbon in H layer remains even in the spruce stand of the 2nd generation.

Translated by the authors

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