Baseline carbon sequestration of forest restoration on burned areas using CO2FIX model

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Abstract. Successful restoration of forests after disturbances is important for the global carbon cycle. In this study, the CO2FIX V3.2 model was used for predictive estimates of carbon sequestration. The results show that both pine plantations and mixed pine-birch forests accumulate similar amounts of carbon in biomass and soil. Mixed stands of pine and birch show slightly higher levels of total carbon sequestration compared to conifer monocultures. Comparatively low levels of carbon sequestration from conventional reforestation practices and the vulnerability of artificial forest plantations to climate change provides the basis for successful implementation of forest carbon projects in the forest steppe region of Oka-Don plain.

1 Introduction

Climate change became one of the most critical global challenges with substantial influences on ecosystems and biodiversity [1]. The carbon balance of natural ecosystems assumes great importance with respect to the regulation of climate change [2]. Carbon sequestration represents an effective mechanism for achieving this goal. It involves the uptake from the atmosphere and long-term carbon storage into plant biomass and soil, which leads to a reduction of greenhouse gas concentrations [3]. The effective management of the carbon balance through nature-based solutions, e.g. reforestation, sustainable agriculture and the protection of natural areas, can significantly enhance the capacity of ecosystems to combat climate change [2].

Forest ecosystems represent one of the largest natural carbon sinks. Successful forest restoration after disturbances where they were not prevented and where natural forest regeneration is limited due to natural factors or climate change consequences is of great importance to the global carbon cycle [4]. The impact of wildfires on forest ecosystems is significant, resulting in the loss of biodiversity and releasing considerable amounts of greenhouse gases into the atmosphere [5, 6]. However, the reforestation of burned areas presents a unique opportunity to enhance carbon sequestration and restore ecosystem functions [4].

The traditional focus of forestry has been on production of timber, but there is increasing recognition of other ecosystem services, such as biodiversity conservation and carbon

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sequestration [7]. Technological and forest management practices that have been effective in the past may not be appropriate in the face of climate change. Therefore, it is crucial to establish a baseline and consider it as a benchmark for comparison with different alternative management scenarios. Furthermore, establishing an ecosystem baseline is required for any nature climate project designed to increase carbon sequestration forests.

The forest steppe ecoregion is characterized by specific climatic and ecological factors that influence the dynamics of post-fire forest regeneration [8]. The study of carbon sequestration in this region is of particular importance for the development of regional climate change mitigation strategies.

The CO2FIX model is an effective tool for assessing carbon sequestration rates in forest ecosystems worldwide. The model permits the simulation of the dynamics of carbon stock in biomass and soil under diverse forest management scenarios [9]. The deployment of this model in forest-steppe conditions can facilitate the acquisition of valuable insights that can contribute to the development of effective forest restoration strategies.

Natural forest regeneration in post-pyrogenic areas is a challenging process in forest-steppe regions, particularly following severe wildfires that result in the mortality of seed trees. Conversely, the widespread practice of artificial reforestation of burned areas, primarily through the establishment of Scots pine monocultures, contributes to elevated forest fire hazard. Smaller areas are characterized by established mixed pine and birch stands in alternating patterns [10].

This study aims to determine the baseline carbon sequestration in forests established by artificial reforestation of burned areas in the forest steppe region of the Oka-Don Plain.

2 Materials and methods

In this study, baseline carbon is defined as the amount of carbon sequestered by growing artificially established stands of Scots pine or mixed stands of pine-birch. This baseline scenario is the most likely in the conditions of the study region, where forest legislation requires forest managers to reforest forests that have been destroyed by wildfire. At the same time, the widespread practice of artificial reforestation is associated with the establishment of pine or pine-birch cultures on the burnt areas.

CO2FIX model V3.2 was used for the prognostic estimates of carbon sequestration. In this study, we focused primarily on the biomass and soil modules and excluded additional modules (products, bioenergy, financing and carbon accounting). Data for model parameterization were obtained from several sources (Table 1).

Table 1. Parameters for estimation of carbon dynamics in pine and pine-birch forests of Forest Steppe of Oka–Don Plain.

Parameters	Scots pine	Birch	References
Wood density (MgDM/m^3)	0.42	0.51	[11]
Stem carbon content (MgC/MgDM)	0.48	0.51	[11]
Foliage carbon content (MgC/MgDM)	0.47	0.47	[11]
Branch carbon content (MgC/MgDM)	0.48	0.51	[11]
Root carbon content (MgC/MgDM)	0.48	0.51	[11]
Foliage turnover rate (year^{-1})	0.18	1.0	[12]
Branch turnover rate (year^{-1})	0.7	0.7	[12]
Root turnover rate (year^{-1})	0.7	0.7	[12]

Growth tables (GT) of modal pine and birch tree stands for ecoregions of zones of mixed and deciduous forests, and forest steppe as well as corresponding tables of biological productivity (TBP) [13] were used as input data for the tree stands. From these tables we

selected values of current annual increment corresponding to the site index of II (determined according to forest plans of the forest-steppe regions of Oka-Don plain) (Table 2). For mixed stands, the current annual increment was calculated as a weighted average of GT for pure stands, where the weight measure is the proportion of different species. Relative to stem growth of foliage, branches and roots for pine and birch was calculated based on TBP (Table 3).

Table 2. Current annual increment for pine and birch.

Age (years)	Scots pine (m^3/ha/year)	Birch (m^3/ha/year)	Age (years)	Scots pine (m^3/ha/year)	Birch (m^3/ha/year)
0	0,00	0,00	60	2,33	0,81
20	5,15	5,62	70	1,76	0,44
30	4,63	4,09	80	1,32	0,24
40	3,82	2,53	90	0,98	0,13
50	3,02	1,46	100	0,73	0,07

Table 3. Relative to stem growth of foliage, branches and roots for pine and birch.

Age (years)	Scots pine			Birch		
	foliage	branches	roots	foliage	branches	roots
0	0,1659	0,2287	0,2825	0,0858	0,2167	0,4289
20	0,1659	0,2287	0,2825	0,0858	0,2167	0,4289
30	0,1184	0,1860	0,2705	0,0604	0,1923	0,3462
40	0,0915	0,1597	0,2646	0,0477	0,1800	0,3015
50	0,0768	0,1419	0,2591	0,0405	0,1744	0,2726
60	0,0660	0,1298	0,2563	0,0353	0,1730	0,2527
70	0,0585	0,1210	0,2537	0,0325	0,1738	0,2388
80	0,0527	0,1135	0,2520	0,0303	0,1772	0,2282
90	0,0477	0,1072	0,2513	0,0292	0,1813	0,2208
100	0,0439	0,1021	0,2504	0,0274	0,1870	0,2153

The soil module utilizes the Yasso model to evaluate the decomposition processes of organic matter and the dynamics of carbon within well-drained forest soils. The model provides an assessment of total organic carbon stocks without differentiating between soil horizons. Monthly temperatures and growing season were specified according to Table 4. Precipitation in growing season was 366.6 mm.

Table 4. Mean temperatures for each month and growing season duration.

Month	T, °C	Growing season	Month	T, °C	Growing season
January	–6.0	No	July	+21.3	Yes
February	–5.5	No	August	+20.2	Yes
March	–0.3	No	September	+13.3	Yes
April	+8.8	Yes	October	+7.5	No
May	+15.5	Yes	November	+0.5	No
June	+19.1	Yes	December	–4.1	No

3 Results and discussion

Figure 1 shows the results of carbon stock modelling in tree stands and soils of pine monocultures and mixed stands of pine and birch with the following composition 70% pine and 30% birch.

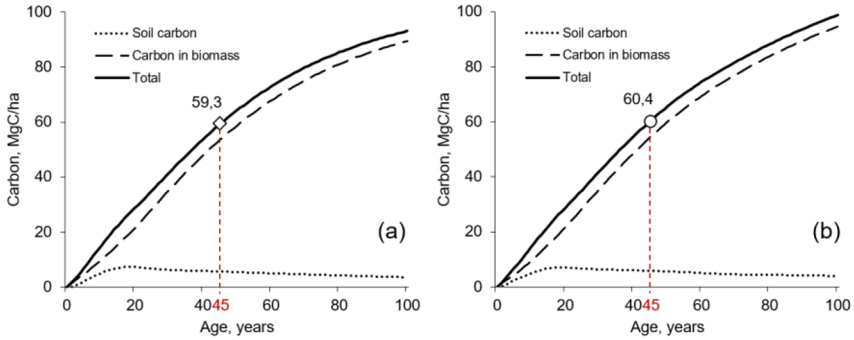

Fig. 1. Carbon sequestration baseline in Scots pine monocultures (a) and mixed pine-birch plantations (b).

The results show that both types of plantations accumulate similar amounts of carbon in both biomass and soil. Pine monocultures accumulate up to 89.5 MgC/ha, including about 4.7 MgC/ha in soil over a 100-year period (Fig. 1a). The average sequestration rate is 0.88 MgC/ha/year, which corresponds to an uptake of 3.23 $MgCO_2$/ha/year. For comparison, previous studies [14] in pine monocultures found that the carbon stock of the stand reached 73.4 MgC/ha by the age of 63 years. According to our estimates using the CO2FIX model, coniferous stands of the same age accumulate similar amounts of carbon in the stand phytomass (70.2 MgC/ha).

However, a more detailed analysis shows that carbon accumulation patterns differ between monocultures and mixed stands. Mixed stands of pine and birch (Fig. 1b) show slightly higher levels of total carbon accumulation up to 100 years of age, reaching 94,8 MgC/ha compared to 89.5 MgC/ha in conifer monocultures. The main differences are due to the higher growth rate and productivity of birch, the introduction of which into the coniferous plantation, even at 30%, increases the average annual level of carbon sequestration in the 100-year horizon by up to 0.99 MgC/ha/year or 3.63 $MgCO_2$/ha/year. Moreover, under similar environmental conditions, there is no significant increase of carbon in the soil carbon pool of these mixed pine-birch plantations – 4.8 MgC/ha.

The most important period for the implementation of forest climate projects is up to 45 years. This is the maximum length of the crediting period for reforestation project activities. During this period, pine monocultures accumulate 59.3 MgC/ha in biomass and soil with an average CO_2 uptake of 4.81 Mg/ha/year. Pine plantations alternating with birch strip plantings provide a total accumulation of up to 60.4 MgC/ha and the average uptake reaches 4.89 Mg/ha/year.

4 Conclusion

Currently, the main value of a forest is as a source of timber, but carbon sequestration can be an important additional value. However, existing management criteria only aim to optimize timber production. Therefore, the current practice of establishing conifer monocultures of economically valuable tree species in the forest steppe zone may not be an effective strategy for carbon sequestration and adaptation to climate change.

This provides the basis for successful implementation of forest carbon projects in the region, as a mixed planting strategy could increase the total carbon sequestration capacity

compared to traditional monoculture practices. For example, annual carbon sequestration can be increased by about 12.4 $MgCO_2$/ha per year in mixed plantations where 50% of the pine is replaced by broadleaves, both fast- and slow-growing [15]. The inclusion of fast-growing poplar is expected to rapidly increase biomass accumulation, thereby accelerating the initial rate of carbon uptake. Meanwhile, the introduction of oak, known for its longevity and dense wood, is expected to contribute to long-term carbon storage both above and below ground.

The results suggest that mixed forest plantations may be more efficient in carbon sequestration than monocultures. This may be due to the synergistic effect of interactions between different tree species, favoring more intensive carbon storage in both biomass and soil. In addition, species diversity may improve the resilience of the ecosystem to external stresses and contribute to a more stable carbon sequestration process. The study results can serve as a basis for a possible assessment of further perspectives for forestry that include the ecological service of carbon sequestration and development of forest restoration strategies.

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