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# Potentially Mineralizable Carbon Dynamics During Post-Agrogenic Succession in Soils of the Leningrad and Novgorod Regions Under Different Land-Use Types

**Roman Dyachkovskiy , Vyacheslav Polyakov *, Timur Nizamutdinov and Evgeny Abakumov**

Department of Applied Ecology, Faculty of Biology, St. Petersburg State University, Universitetskaya Embankment, 7/9, St. Petersburg 199034, Russia; r.dyachkovskiy@spbu.ru (R.D.); t.nizamutdinov@spbu.ru (T.N.); e.abakumov@spbu.ru (E.A.)

* Correspondence: v.polyakov@spbu.ru

**Abstract**

Agricultural lands in Russia are increasingly being converted into fallow areas, making the study of potentially mineralizable carbon (PMC) in fallow soils essential for understanding post-agrogenic ecosystem functioning. This study provides a comparative assessment of the spatial and temporal dynamics of PMC in soils of the Leningrad and Novgorod regions (Bankovo, Belogorka, and Borovichi sites) under different land-use types, including fallows of various ages, arable, garden, pasture, hayfield soils, and secondary forests. Total carbon content was determined by high-temperature dry combustion, while basal respiration was measured using a standard incubation method. PMC parameters were estimated using biokinetic fractionation of soil organic matter (SOM), and cumulative carbon release was calculated as the sum of emissions over the incubation period. The highest basal respiration values among the studied fallow soils were observed in fallow soils at the Bankovo site (1.44–1.66 μg $CO_2$–C $g^{-1}$ $h^{-1}$). Carbon stocks in most fallow soils were lower than those of the corresponding background soils, although the magnitude of differences varied among sites. Both the size of the PMC pool and its mineralization rate varied among fallow soils depending on post-agrogenic succession, vegetation type, and site-specific environmental conditions. The highest cumulative C-$CO_2$ production was recorded in degraded pasture soils and secondary forests at Borovichi. Restorative ecosystems generally showed higher carbon-mineralizing activity than arable and garden soils, although turnover characteristics varied among sites. Region-specific patterns related to parent material and environmental conditions were identified. Even after long-term fallowing (up to 120 years), several soil properties remained different from background conditions, indicating prolonged and site-dependent recovery of organic matter dynamics.

**Keywords:** post-agrogenic dynamics; fallow soils; carbon pool; carbon-mineralizing activity; biokinetic fractionation; Northwestern Russia



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## 1. Introduction

Potentially mineralizable carbon (PMC) serves as a key indicator of soil biological activity and characterizes the size of the pool of organic matter available for microbial mineralization [1]. In conditions of widespread withdrawal of agricultural lands from active turnover, the study of PMC dynamics in fallow soils gains particular relevance for understanding the patterns of post-agrogenic ecosystem dynamics [2]. Methods of biokinetic fractionation enable the determination of PMC size and the mineralization rate constant, thereby allowing quantitative assessment of the turnover rate of labile organic matter in soil [3].

Abandonment of agricultural lands represents a significant problem in European countries [4–7]. The global area of abandoned lands totals 220 million hectares, of which Russia accounts for nearly 20% [8]. Since the early 1990s, Russian agriculture has exhibited a persistent trend of withdrawing previously sown arable lands from active agricultural turnover [2,9,10]. The current state of agricultural lands in Russia is characterized by the widespread conversion of significant areas into fallow condition. Despite Russia holding the first place worldwide in land resource availability and ranking among the top five leaders in arable land area, up to 40 out of 120 million hectares have currently been excluded from agricultural practice [2,11]. Concomitantly with restoration of zonal vegetation during post-agrogenic evolution, changes occur in soil biological properties [12,13], underscoring the need to investigate biochemical activity of fallow land territories, as they represent a "hidden" food basket of Eurasia.

Fallow lands undergo transformation under the influence of natural and anthropogenic processes. Soil microorganisms are regarded as key factors in the restoration of degraded lands [14,15]. Upon conversion of lands to fallow, carbon accumulation or loss may occur, depending on the initial soil state, its genesis, parent material, and historical land use conditions [16]. Certain studies have demonstrated that cessation of agriculture and initiation of natural succession lead to increased input of plant residues and reduced losses of organic matter, thereby promoting accumulation of soil organic matter (SOM) [17,18]. Accumulation of SOM enhances the stability of the soil cover, improves soil structure and water-physical properties, and results in decreased $CO_2$ emissions to the atmosphere, which is critical in the context of climate regulation.

However, without proper restoration of fallow landscapes (with short-term withdrawal of land, gardens, pasture, hayfields, secondary forest), or with a return to cultivation, the expected carbon accumulation is not realized. SOM accumulation may be minimal or even involve losses. Furthermore, SOM accumulation rates may substantially decline over time after ~10–20 years, upon reaching "saturation" of the carbon pool [5,10].

Although SOM content provides important information on the overall accumulation of organic matter during post-agrogenic succession, it may not fully reflect changes in the biological availability and turnover of organic carbon in soil during post-agrogenic succession. In this context, PMC provides complementary information on total SOM content. While SOM represents a broad pool of organic matter in soil, PMC characterizes the fraction that is potentially available for microbial mineralization. Changes in PMC and its mineralization kinetics may provide additional information on the transformation and turnover of soil organic matter during succession. This approach may help identify changes in soil carbon dynamics that are not necessarily reflected by changes in total SOM content alone.

The present study focuses on three typical sites in Northwest Russia: Belogorka (Leningrad Region), Bankovo (Leningrad Region) and Borovichi (Novgorod Region). These sites feature characteristic soil types for the respective regions and reflect principal land use patterns. The research objective is to investigate changes in PMC and the associated kinetic parameters of organic matter mineralization in the studied territories in order to assess the dynamics of soil organic carbon during post-agrogenic succession. To achieve this goal, the soil and environmental conditions of the study areas were characterized, soil microbial activity was assessed, and the size of the PMC pool and the kinetic parameters of organic matter mineralization were evaluated for soils of fallow lands of different ages, as well as fallow territories used as gardens, pasture, and hayfield, and reference sites, based on laboratory incubation experiments.

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## 2. Materials and Methods

### *2.1. Study Area*

The study was conducted at 13 sites located in the Leningrad and Novgorod regions, representing different land-use types: background (benchmark forest) sites (*n* = 3) (Belogorka background, Bankovo background, Borovichi background), arable soils (*n* = 1) (Belogorka arable soils), and fallow lands of different ages (*n* = 4) (Belogorka fallow, Bankovo fallow of 40, 80, and 120 years). In addition, other land-use types were investigated (*n* = 5), including vegetable gardens (2), secondary forest (1), pasture (1), and hayfield (1) (Figure 1). These sites were abandoned in 1993 and subsequently converted to gardens, pasture, hayfields, or secondary forest.

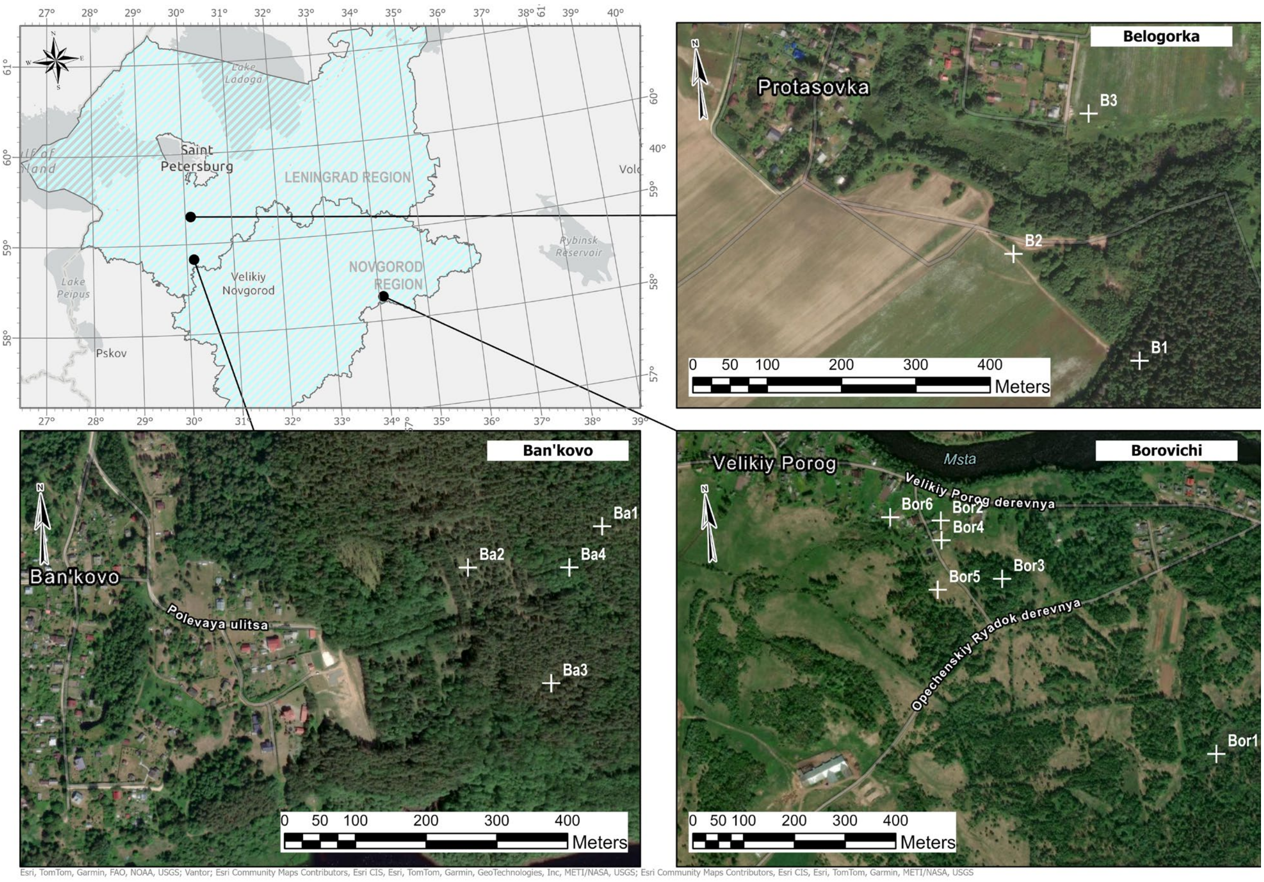


**Figure 1.** Map of soil sampling locations.

The upper humus horizons of the soils were examined. A brief description of the sampling sites is provided in Table 1.

**Table 1.** Description of the studied soil horizons.

| Soil ID | Horizon * | Depth, cm | Description | Vegetation | Location | Soil Name ** |
|---|---|---|---|---|---|---|
| | | | | Belogorka | | |
| B1 | A/E | 5–25 | Transitional mineral horizon exhibiting both the accumulation of humified organic matter and the eluviation of silicate clays | Bilberry spruce forest | Benchmark forest, background soil | Retisol (loamic) |
| B2 | Ap | 0–42 | Mineral horizon characterized by the accumulation of humified organic matter | Cereal crops | Agriculture lands | Plaggic Retisol (loamic) |

**Table 1.** *Cont.*

| Soil ID | Horizon * | Depth, cm | Description | Vegetation | Location | Soil Name ** |
|---|---|---|---|---|---|---|
| B3 | Ap | 2–34 | Mineral horizon characterized by the accumulation of humified organic matter | Grass herbaceous communities with individual rowan shrubs | 20 years old fallow lands | Plaggic Retisol (loamic) |
| | | | | Bankovo | | |
| Ba1 | $E_1$ | 4–10 | Mineral horizon exhibiting pronounced eluviation of silicate clays and iron oxides, manifested in a distinctly light coloration | Lighted bilberry pine-birch forest | Benchmark forest, background soil | Stagnic Podzol (arenic) |
| Ba2 | Ap | 0–30 | Mineral horizon characterized by the accumulation of humified organic matter | Herbaceous meadow with scattered pine trees | 40 years old fallow lands | Plaggic Podzol (arenic) |
| Ba3 | Ap | 0–30 | Mineral horizon characterized by the accumulation of humified organic matter | Lighted herbaceous pine forest | 80 years old fallow lands | Plaggic Podzol (arenic) |
| Ba4 | Ap | 3–28 | Mineral horizon characterized by the accumulation of humified organic matter | Alder-birch forest | 120 years old fallow lands | Plaggic Podzol (arenic) |
| | | | | Borovichi | | |
| Bor1 | Ah | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Bilberry spruce forest | Benchmark forest, background soil | Podzol (arenic) |
| Bor2 | Ap | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Garden with shrubs and trees | Garden established on land that had been fallow for 30 years | Plaggic Podzol (arenic) |
| Bor3 | Ap | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Bilberry pine-birch forest | Secondary forest established on land that had been fallow for 30 years | Plaggic Podzol (arenic) |
| Bor4 | Ap | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Herbaceous meadow | Pasture established on land that had been fallow for 30 years | Plaggic Podzol (arenic) |
| Bor5 | Ap | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Herbaceous meadow | Hayfield established on land that had been fallow for 30 years | Plaggic Podzol (arenic) |
| Bor6 | Ap | 0–30 | Mineral horizon distinguished by the accumulation of humified organic matter | Cereal crops | 130 years old agriculture land | Plaggic Podzol (arenic) |

* Jahn et al. [19]; ** IUSS WRB. [20].

The study area of Leningrad and Novgorod regions is confined to the periglacial zone of the Valdai glaciation and is characterized by the widespread development of moraine complexes [21]. The relief is predominantly flat, with relative elevation differences of about 20 m. The soil cover of the studied area is mainly represented by automorphic and hydromorphic soils formed on sandy and sandy loam substrates [22]. Podzols and sod-podzolic soils (Retisols) prevail on watersheds, their formation being driven by pronounced eluviation processes and the removal of mobile compounds. In relief depressions, under conditions of stagnant moisture, gley horizons and peat deposits develop, reflecting a hydromorphic type of pedogenesis.

The Leningrad Region is located in the northwestern part of the East European Plain. The relief is dominated by glaciofluvial landforms associated with the Valdai glaciation. Most of the territory lies at elevations below 100 m. In the western part of the Leningrad Region, the climate is transitional from maritime to moderately continental, while in the eastern part it is moderately continental. Winters are mild with frequent thaws, and summers are moderately warm (17.5–19 °C in July). The region is located within a zone of excessive moisture, with annual precipitation of 680–760 mm [23]. The Novgorod Region is located in the northwestern part of the East European Plain. Its western part is occupied by the leveled lacustrine–glacial Ilmen Lowland, with absolute elevations ranging from 20 to 100 m. Within this area, moraine and glaciofluvial ridges occur. The eastern part is represented by the Valdai Hills. The climate of the Novgorod Region is moderately continental. The period with active temperatures above 10 °C lasts 110–135 days. Winters are relatively mild, with frequent thaws and short periods of frost. The mean July temperature is 16–18 °C. Annual precipitation amounts to 600–800 mm [23].

Fallow lands of different ages and agricultural use types are widely distributed in the Leningrad and Novgorod regions [13]. In the vicinity of the village of Bankovo, fallow soils aged 40–120 years are found. The parent materials are represented by dense glaciofluvial sandy loams underlain at depths of 70–80 cm by reddish-brown moraine loams. The natural vegetation of the area consists of pine–birch forests with blackberry in the understory. In the Belogorka area, soils of 20-year-old fallows, as well as arable and undisturbed sites, were studied. The relief of the territory is close to leveled. The parent materials are represented by red-colored moraines with admixtures of Devonian clays. The area belongs to the southern taiga subzone, where pine forests dominate, with admixtures of spruce, birch, and aspen. In the vicinity of Borovichi, 30-year-old fallow soils, as well as arable and undisturbed sites, were investigated. The parent materials are represented by glaciofluvial sands. Studies of the microbiomes of fallow soils in the southern taiga of the Novgorod Region have revealed significant differences in the structure and functioning of microbial communities depending on the type of post-agrogenic land use [11]. All key plots are confined to a single agrolandscape of a former agricultural enterprise, which ensures the comparability of the study conditions.

The selection of the study sites was determined by the need to compare pedogenetic processes in fallow soils formed on different parent materials: sandy substrates (Bankovo) and loamy–clayey moraines (Belogorka). In addition, the sites in the Novgorod Region (Borovichi) make it possible to analyze soil transformation following land abandonment 30 years ago under different forms of agricultural land use. This approach allows for the evaluation of post-agrogenic soil transformation rates across contrasting lithological, geomorphological, and bioclimatic settings in the Leningrad and Novgorod regions, where soils at different stages of fallow succession occur in close spatial proximity.

### *2.2. Sampling Strategy*

Field sampling was carried out during the summer of 2023. Soil samples were collected from the topsoil horizons (A and E). The sampling depth ranged from 0 to 42 cm and varied depending on the presence and intensity of soil processes associated with the transition to the fallow state. Five individual subsamples were taken from the soil horizon and homogenized to obtain a representative composite sample. Soil samples were collected with sterilized instruments in sterilized bags with a volume of 1 or 2 liters. For bulk density determination, three undisturbed soil samples were additionally collected from the upper humus horizon at each sampling site using cylinders of known volume. Bulk density was determined separately for each sample, and the mean value of the three measurements was used for subsequent calculations. Soil classification and identification of diagnostic features were performed in accordance with the World Reference Base for Soil Resources (WRB) [20] and the FAO Guidelines for Soil Description [19].

Samples intended for chemical analyses were stored at +4 °C (for 1 week) to preserve their physicochemical properties prior to laboratory processing. Before analysis, soil samples were air-dried, gently ground, and passed through a 2 mm sieve to obtain the fine earth fraction. The prepared samples were subsequently used for the determination of PMC parameters, basic physicochemical properties, and related analyses.

### 2.3. Laboratory Methods

Each homogenized composite sample was divided into three analytical subsamples by quartering, which were used as analytical replicates for laboratory measurements.

In laboratory conditions, pH values were determined by the potentiometric method using a pH analyzer Milwaukee Mi106 (Milwaukee Electronics, Portland, OR, USA) [24]. Total carbon content was measured by high-temperature dry combustion using a LECO TruSpec MICRO elemental analyzer (St. Joseph, MI, USA) at the Chemical Analysis and Materials Research Centre of the Research Park of St. Petersburg State University according to the FAO methodology [25].

Soil carbon stock (t/ha) was calculated using the formula:

$$C = C_{total} \times H \times \rho \quad (1)$$

where $C$ is the carbon stock in the soil pool (t C/ha), $C_{total}$ is the total carbon content in soil (%), $H$ is the thickness of the soil layer (horizon) (cm), and $\rho$ is the bulk density of soil (g/cm$^3$) [26]. Soil bulk density was determined using undisturbed soil samples collected in cylinders of known volume. The samples were oven-dried at 105 ± 5 °C to constant mass and weighed. Bulk density was calculated as the ratio of the oven-dry soil mass to the volume of the cylinder [27].

Microbial activity, expressed as basal respiration (*BR*), was assessed using the method proposed by J. Bloem et al. [28]. Soil samples were sieved through a 2 mm mesh and adjusted to 50–70% of water-holding capacity. The samples were placed in hermetically sealed 1 L glass jars and pre-incubated at 22 °C for 10 days. Three control samples were prepared in the same way but without soil. At the end of the pre-incubation period, a vial containing 2 mL of 0.1 M NaOH solution was placed in the same jar without contact with the soil, followed by incubation at 22 °C for 24 h. The amount of released $CO_2$ was calculated from the difference in the volume of acid used for titration of the control and experimental samples according to the formula:

$$BR = \frac{(B - S) \times 12.01 \times 0.05}{w \times t \times 2} \times 10^3 \quad (2)$$

where $BR$ is soil basal respiration (μg $CO_2$–C g$^{-1}$ h$^{-1}$), $B$ is the volume of HCl (0.05 M) used to titrate the control solution (mL), S is the volume of HCl (0.05 M) used to titrate the sample (mL), w is the dry soil mass (g), and $t$ is the incubation time (h).

The parameters of PMC were determined using the biokinetic fractionation method of SOM in triplicate [29–31]. Prior to the experiment, soil samples were pre-incubated at 22 °C for 7 days to stabilize microbial activity. Subsequent incubation was carried out at a constant temperature of 22 °C and at 25% of water-holding capacity for 174 days. During the incubation, periodic measurements of carbon dioxide release were performed. The concentration of C–$CO_2$ in the vials was determined by the titrimetric method.

Cumulative carbon release (μg C–$CO_2$/g) was calculated by summing the values recorded at each observation time point, taking into account the accumulated amount from previous measurements. The dynamics of C–$CO_2$ release over the entire experimental period were approximated using a one-component first-order kinetic equation:

$$C(t) = C_{pm} \times \left(1 - ^{-kt}\right) \quad (3)$$

where $C(t)$ is the cumulative amount of released C–$CO_2$ (μg C–$CO_2$/g soil) over time t (days), $C_{pm}$ is the size of the potentially mineralizable carbon pool (μg C/g soil), and k is the rate constant of SOM mineralization (day$^{-1}$).

The mean turnover time of the pool was calculated as T = $1/k$ [32].

Biokinetic parameters $C_{pm}$ and $k$ were calculated using nonlinear regression (second-degree polynomial regression) implemented in Prism 10.2.2.397 (GraphPad Software, v10.2.2.397). Carbon-mineralizing activity (CA) of soils was assessed using an index obtained by multiplying the PMC content by the mineralization rate constant ($C_{pm}k$, mg 100 g $^{-1}$ day $^{-1}$) [33].

Cartographic schemes were produced using licensed ArcGIS Pro software (v3.0.1.) (Esri, Redlands, CA, USA).

## 3. Results

### 3.1. Physic-Chemical Characteristics of Studied Soil

For each studied area, the dynamics of key soil parameters reflecting recovery processes and changes after the transition to fallow land were obtained (Table 2).

**Table 2.** Soil properties of the studied fallow areas.

| Fallow Age (Years) | pH | *BR* (μg $CO_2$–C $g^{-1}$ $h^{-1}$) | C (%) |
|---|---|---|---|
| | Belogorka | | |
| Background soil (B1) | 4.42 | 1.28 | 2.28 |
| Agriculture land (B2) | 5.66 | 0.45 | 1.48 |
| 20 (B3) | 4.87 | 0.09 | 1.44 |
| | Bankovo | | |
| Background soil (Ba1) | 4.98 | 0.25 | 4.98 |
| 40 (Ba2) | 5.89 | 1.44 | 1.44 |
| 80 (Ba3) | 5.68 | 1.63 | 0.62 |
| 120 (Ba4) | 5.64 | 1.66 | 1.39 |
| | Borovichi | | |
| Background soil (Bor1) | 5.73 | 0.82 | 3.77 |
| 30 (Bor2) | 6.11 | 0.05 | 1.40 |
| 30 (Bor3) | 6.67 | 2.03 | 2.55 |
| 30 (Bor4) | 6.37 | 1.60 | 2.42 |
| 30 (Bor5) | 6.23 | 1.45 | 2.21 |
| 130 agriculture land (Bor6) | 6.87 | 1.27 | 0.83 |

Soil pH varied among the study sites and fallow ages. At Belogorka, the 20-year-old fallow had a lower pH than the agricultural soil and the background soil. At Bankovo, pH values varied only moderately among the 40-, 80-, and 120-year-old fallows. At Borovichi, the four 30-year-old fallow sites showed relatively similar pH values, whereas the agricultural soil had the highest pH.

The observed *BR* patterns varied substantially among the study sites. At Belogorka, *BR* decreased following agricultural abandonment and was lower in the 20-year-old fallow than in both the background forest and the agricultural soil. In contrast, *BR* values at Bankovo were considerably higher than in the corresponding background forest and showed a slight increase with increasing fallow age. At Borovichi, *BR* values in three of the four 30-year-old fallow samples were higher than the background value, whereas Bor2 showed a pronounced local deviation with a markedly lower *BR*. Thus, the results did not indicate a consistent pattern of *BR* dynamics following agricultural abandonment across the studied sites.

With respect to C%, fallow soils generally showed lower carbon concentrations than the corresponding background soils. This pattern was observed at all three study sites, although C% did not show a consistent relationship with the duration of the post-agrogenic period.

Soil organic carbon stocks showed considerable variation among the studied sites (Figure 2).

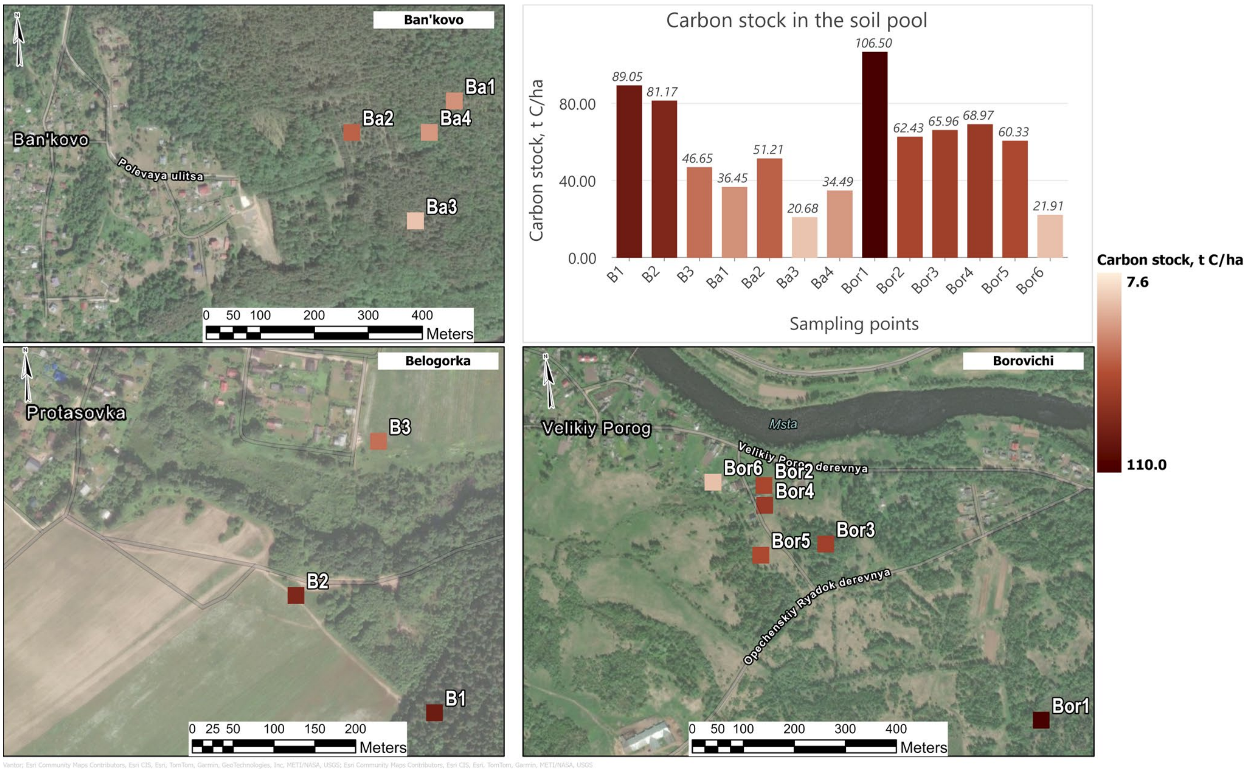


**Figure 2.** Soil carbon stocks in the upper humus horizons of fallow soils.

At Belogorka, the 20-year-old fallow had a lower carbon stock than the background soil. At Bankovo, carbon stocks varied considerably with fallow age. The 40-year-old fallow had a higher carbon stock than the background soil, whereas the 80- and 120-year-old fallows had lower values, with the 80-year-old fallow showing the lowest carbon stock among the Bankovo sites. At Borovichi, the four 30-year-old fallow sites had consistently lower carbon stocks than the background soil, although the values were relatively similar among the sites. The agricultural site had the lowest carbon stock among all Borovichi sites.

### *3.2. Potentially Mineralizable Carbon and Carbon Mineralization Kinetics*

Laboratory incubation experiments showed considerable variation in cumulative C–$CO_2$ production among the studied soils and land-use types (Figure 3).

After 174 days of incubation, the lowest mean values were observed for the 40-year-old fallow soils at Bankovo (440.0 ± 63.7 μg C–$CO_2$/g) and for the agricultural soil at Borovichi (468.2 ± 188.9 μg C–$CO_2$/g). The highest mean C–$CO_2$ emission values were recorded in pasture soils at Borovichi (2672.7 ± 481.8 μg C–$CO_2$/g), secondary forest soils at Borovichi (2172.8 ± 565.4 μg C–$CO_2$/g), and hayfield soils at Borovichi (2064.0 ± 363.0 μg C–$CO_2$/g). The background forest soils also showed considerable variation among the study sites, with mean C–$CO_2$ emission values of 1757.3 ± 279.9 μg C–$CO_2$/g at Belogorka, 1224.5 ± 304.0 μg C–$CO_2$/g at Bankovo, and 1141.1 ± 518.8 μg C–$CO_2$/g at Borovichi. This variation may be related to differences in parent materials and microclimatic conditions [34].

The kinetic parameters of organic matter mineralization also varied among the studied soils (Table 3). Sites under secondary forest, hayfield, and pasture showed relatively high CA values, whereas lower CA values were observed in the agricultural and garden soils.

The *k* and T values varied considerably among the fallow soils. At Bankovo, the 40- and 80-year-old fallows had relatively short turnover times, whereas the 120-year-old fallow had a longer turnover time. The 20-year-old fallow at Belogorka also had a relatively short turnover time, while the fallow soils at Borovichi showed longer turnover times.

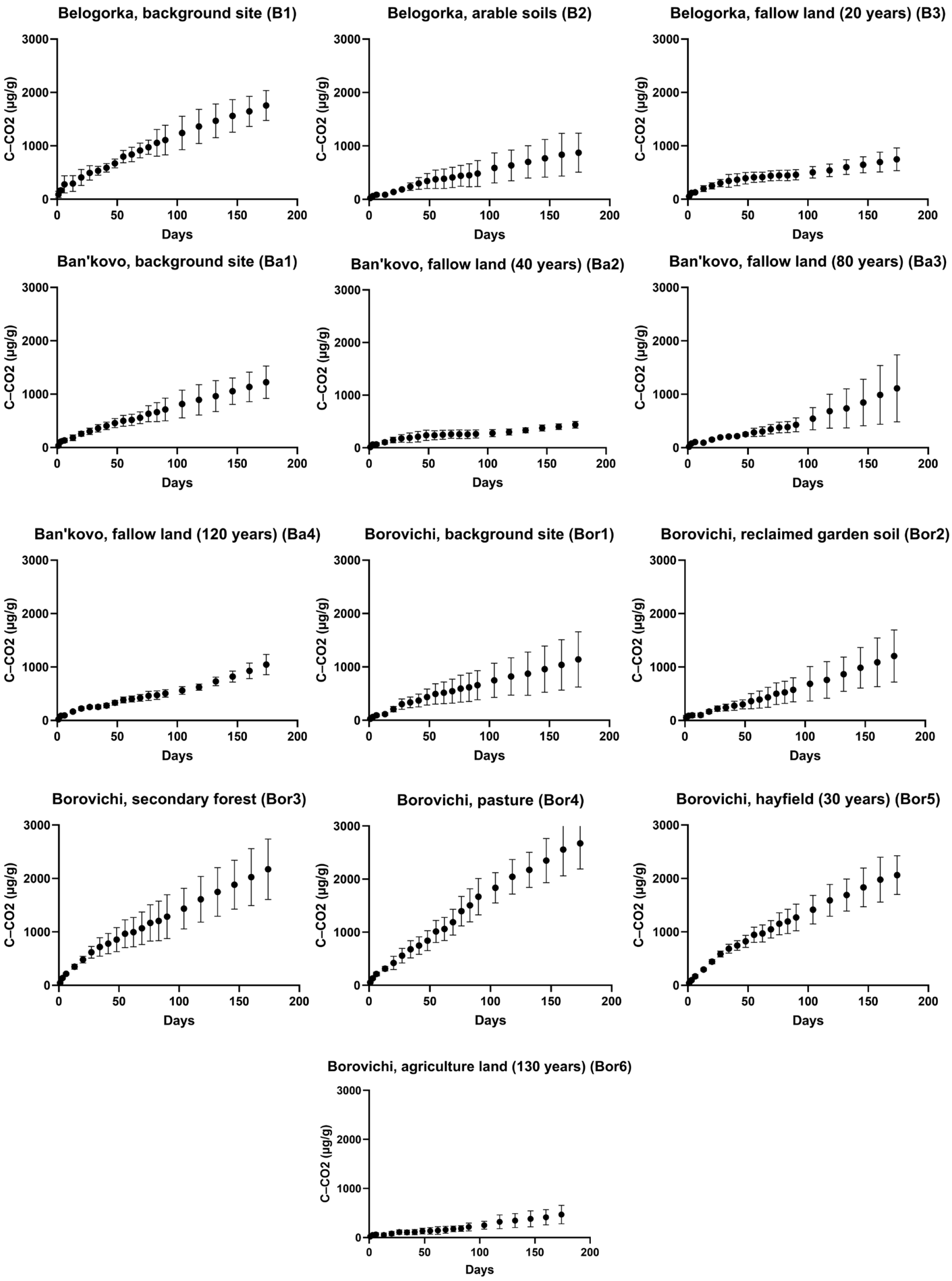


**Figure 3.** Cumulative C–$CO_2$ production curves for soils of the Leningrad and Novgorod Regions under different land-use types (mean values; error bars indicate standard deviation, ±SD, n = 3).

The cumulative C-$CO_2$ production showed considerable variation among the studied soils and land-use types. The highest values were observed in the pasture and secondary forest soils at Borovichi, followed by the hayfield soil. The background soil at Belogorka also showed a relatively high C-$CO_2$ production, whereas lower values were observed in the fallow soils at Bankovo, particularly in the 40- and 80-year-old fallows. The garden soil at Borovichi showed a comparatively low C-$CO_2$ production.

**Table 3.** Parameters of the organic matter pool.

| ID | Description | CA, mg 100 g $^{-1}$ day $^{-1}$ | *k*, day $^{-1}$ | T, days |
|---|---|---|---|---|
| B1 | Background site | 17.26 | 0.007 | 139.7 |
| B2 | Arable soils | 7.08 | 0.005 | 214.9 |
| B3 | Fallow land (20 years) | 12.26 | 0.020 | 52.6 |
| Ba1 | Background site | 10.42 | 0.006 | 180.3 |
| Ba2 | Fallow land (40 years) | 7.40 | 0.010 | 57.5 |
| Ba3 | Fallow land (80 years) | 6.35 | 0.020 | 59.4 |
| Ba4 | Fallow land (120 years) | 7.79 | 0.005 | 190.7 |
| Bor1 | Background site | 9.98 | 0.007 | 141.2 |
| Bor2 | Garden (after 30-year fallow) | 7.04 | 0.006 | 172.8 |
| Bor3 | Secondary forest (after 30-year fallow) | 20.27 | 0.007 | 148.9 |
| Bor4 | Pasture after 30-year fallow | 20.53 | 0.003 | 302.7 |
| Bor5 | Hayfield (after 30-year fallow) | 20.00 | 0.007 | 140.3 |
| Bor6 | Agriculture land (130 years) | 3.13 | 0.004 | 242.4 |

The $C_{pm}$ values also varied considerably among the studied sites (Figure 4). At Bankovo, the 40- and 80-year-old fallows had lower $C_{pm}$ values than the 120-year-old fallow. At Borovichi, the secondary forest, pasture, and hayfield soils had relatively high $C_{pm}$ values, whereas the garden and agricultural soils had lower values. Analysis of the chronosequence of fallow soils at Bankovo did not reveal a clear dependence of PMC on fallow age: 40-year-old fallow, $C_{pm}$ = 586.36 mg/kg; 80-year-old fallow, $C_{pm}$ = 377.18 mg/kg; and 120-year-old fallow, $C_{pm}$ = 1602.98 mg/kg. The $C_{pm}$ pool was substantially larger in the 120-year-old fallow than in the 40- and 80-year-old fallows, while the mineralization rate constant and mean turnover time also differed among the three fallow ages.

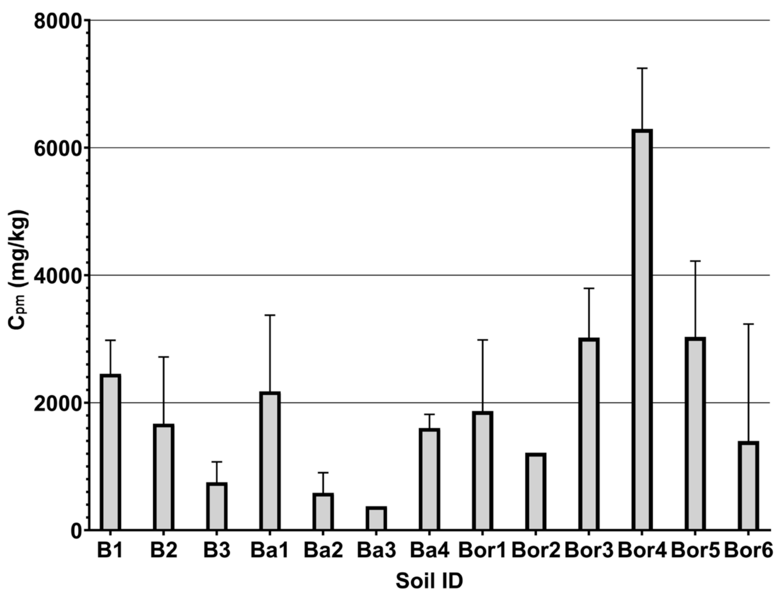


**Figure 4.** Parameters of $C_{pm}$ for the surveyed sites (mean values; error bars indicate standard deviation, ±SD). A detailed description of the land-use types is provided in Table 3.

## 4. Discussion

### *4.1. Changes in Soil Properties and Carbon Stocks During Post-Agrogenic Succession*

The pH values of fallow soils were generally lower than those of the corresponding agricultural soils, suggesting a gradual decrease in soil pH following the abandonment of agricultural land. However, no consistent relationship between pH and fallow age was observed across the study sites. The extent of these changes varied among sites, likely reflecting differences in initial soil properties and previous agricultural management. During the first thirty years, abandoned soils may retain a considerable buffering capacity, even under previous fertilizer application, which could delay soil acidification [16]. The obtained results were consistent with the findings reported by Litvinovich [35] and Abakumov et al. [11].

Fallow soils generally showed lower carbon concentrations than the corresponding background soils, although C% did not show a consistent relationship with the duration of the post-agrogenic period. The lower C% in fallow soils relative to the background soils may be related to changes in carbon inputs and allocation during post-agrogenic succession. As succession proceeds, the plant community gradually approaches a natural ecosystem, which may be accompanied by changes in the quantity and quality of organic matter inputs to the soil and in decomposition processes [36]. A proportion of carbon may also be retained in woody biomass and forest litter rather than being incorporated into the mineral soil.

The observed variation in soil organic carbon stocks among the fallow sites suggests that carbon recovery during post-agrogenic succession was not uniform and did not follow a simple increase with fallow age. These results are consistent with findings reported by other authors [37]. For example, according to Kurganova et al., soil organic carbon stock in the 0–20 cm layer of 20-year-old fallows in the southern taiga amounted to 47.8 t C/ha. In arable soils with shallow humus-accumulative horizons, carbon stocks in the plough layer may be lower than in their natural counterparts due to ploughing and mixing with underlying subsoil horizons.

Thus, the present results support the view that agricultural abandonment does not necessarily result in a uniform increase in soil carbon stocks. The direction and magnitude of carbon changes may depend on initial soil conditions, previous land use, vegetation development, and site-specific environmental conditions [16–18].

### *4.2. Microbial Activity During Post-Agrogenic Succession*

The observed *BR* patterns varied substantially among the study sites. At Belogorka, *BR* decreased following agricultural abandonment, whereas at Bankovo *BR* values were higher than in the corresponding background forest. At Borovichi, most of the 30-year-old fallow soils also showed higher *BR* than the background soil, while Bor2 represented a pronounced local deviation. Thus, the results did not indicate a consistent pattern of *BR* dynamics following agricultural abandonment across the studied sites.

The low *BR* observed at the Belogorka fallow site may be associated with the limited availability of easily decomposable organic substrates during the early stages of post-agricultural succession. Following the cessation of agricultural use, the input of readily decomposable compounds associated with cultivated plants and agricultural management may decrease, potentially reducing microbial respiration. In addition, the formation of stable organo-mineral complexes may reduce the availability of soil organic matter to microorganisms [36].

However, these mechanisms cannot fully explain the elevated *BR* values observed at Bankovo and Borovichi. At Bankovo, the long post-agrogenic period may have allowed vegetation succession to restore litter inputs, root biomass, and an active microbial community. The continuous input of relatively labile organic substrates associated with established vegetation may therefore have supported relatively high microbial respiration. Similar increases in microbial biomass and basal respiration during the transition from arable lands to mature forests have been reported in studies of post-agrogenic soils in the European part of Russia [37,38].

The differences between fallow and background soils may therefore reflect not only fallow age but also site-specific soil properties and differences in the trajectory of vegetation recovery.

*4.3. Potentially Mineralizable Carbon and Carbon Mineralization Kinetics*

The results demonstrate considerable variation in PMC and carbon mineralization kinetics among the studied soils. Importantly, these parameters did not show a simple relationship with fallow age. This was particularly evident at Bankovo, where the 40-, 80-, and 120-year-old fallows differed considerably in $C_{pm}$, $k$, and T.

Sites undergoing restorative succession, including secondary forest, hayfield, and pasture, showed relatively high CA values, whereas agricultural and garden soils generally had lower CA values. This pattern may reflect differences in the quantity and quality of organic substrates supplied by vegetation and differences in microbial activity under different land-use types.

The fallow soils showed considerable variation in turnover time and mineralization rate. At Bankovo, the younger fallows had relatively short turnover times, whereas the 120-year-old fallow showed a longer turnover time. The k values similarly varied among the fallow sites. These differences may reflect variation in the quantity and quality of organic substrates, vegetation biomass and composition, and other site-specific environmental conditions affecting microbial activity and organic matter decomposition [31].

The absence of a simple chronosequence at Bankovo suggests that fallow age alone cannot explain the dynamics of the potentially mineralizable carbon pool. The substantially larger PMC pool in the 120-year-old fallow may reflect changes in vegetation development and organic matter inputs during long-term succession. At the same time, the larger pool was accompanied by a lower mineralization rate constant and longer turnover time, indicating that pool size and turnover rate did not change synchronously during succession.

Importantly, the observed differences in PMC-related parameters were not always directly reflected by total C%. This supports the use of PMC as a complementary indicator of soil carbon dynamics. While total soil carbon describes the overall organic carbon pool, PMC characterizes the fraction potentially available for microbial mineralization. Therefore, changes in PMC and its mineralization kinetics may provide additional information on the biological availability and turnover of soil organic carbon during post-agrogenic succession.

*4.4. Influence of Land-Use History and Site-Specific Conditions*

The differences observed among Belogorka, Bankovo, and Borovichi indicate that post-agrogenic soil development was strongly influenced by local environmental conditions and land-use history. This was particularly evident at Borovichi, where areas sharing a 30-year fallow history subsequently developed under different land-use types. Secondary forest, hayfield, and pasture showed relatively high carbon mineralization activity, whereas garden and agricultural soils showed lower values.

These differences demonstrate that the subsequent trajectory of land use may be as important as the duration of the initial fallow period in determining soil carbon dynamics. Thus, the results do not support a simple chronosequence in which increasing fallow age alone leads to progressive recovery of soil carbon pools and microbial activity.

Overall, the results indicate that post-agrogenic succession was accompanied by substantial changes in soil carbon dynamics, but these changes were not consistently related to fallow age. Instead, the observed patterns of pH, *BR*, carbon stocks, PMC, and mineralization kinetics likely reflect the interaction of fallow duration with vegetation development, land-use history, organic substrate availability, and site-specific soil and environmental conditions.

## 5. Conclusions

The conducted research demonstrated that post-agrogenic transformation of soils in Northwestern Russia is a complex process controlled by the interaction of land-use history, duration of abandonment, vegetation recovery, and site-specific soil conditions. The studied fallow soils did not show a uniform trajectory of ecosystem recovery, indicating that the restoration of soil properties after agricultural abandonment is not determined by fallow age alone.

Changes in soil chemical and biological characteristics reflected different stages and pathways of post-agrogenic development. Soil acidity, carbon content, and microbial activity varied considerably among the studied sites, while differences between fallow and background soils demonstrated that the recovery of soil properties may proceed at different rates depending on initial soil conditions and previous agricultural management. Therefore, the transition from agricultural land to natural or semi-natural ecosystems should be considered as a site-specific process rather than a predictable chronosequence.

The assessment of potentially mineralizable carbon and mineralization kinetics provided additional information on soil organic matter dynamics and revealed differences in the biological functioning of soils under various land-use types. The results showed that the size and turnover rate of the labile carbon pool were influenced not only by the duration of the post-agrogenic period but also by vegetation composition and environmental conditions. Thus, PMC parameters can serve as complementary indicators for evaluating changes in soil carbon cycling during ecosystem recovery.

Overall, fallow lands of Northwestern Russia represent important elements of regional carbon dynamics and may contribute to the restoration of soil functions after agricultural abandonment. However, their potential for carbon accumulation and stabilization depends on the combination of natural succession processes and local environmental constraints. Consideration of regional soil characteristics and land-use history is therefore essential for accurate assessment of carbon sequestration potential and sustainable management of abandoned agricultural territories.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| SOM | Soil organic matter |
| IUSS WRB | International Union of Soil Sciences World Reference Base for Soil Resources |
| PMC | Potentially mineralizable carbon |

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