Carbon balance in case of short-term green manure of a fallow in the conditions of the Baikal forest-steppe

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Abstract. Changes in carbon balance during short-term green manure of a fallow in the conditions of the forest-steppe zone of the Baikal region are studied on the basis of the results of three-year field experiments. It was revealed that the introduction of green mass of oilseed radish (Raphanus sativus var. Oleifera Metzg) into gray forest soil at the end of the summer period significantly activates the processes of mineralization. The total CO₂ emission from the soil surface in the variants with green manure increases by 1.3–1.6 times as compared with pure fallow. Compensation of gaseous carbon losses due to newly introduced organic matter is possible only at high yields of oilseed radish (3-5 tons of dry matter per ha) and hydrothermal conditions unfavourable for its mineralization. Under favourable conditions for the mineralization of fresh organic matter, a negative carbon balance is formed, but its value remains less deficient than in the variants of pure fallow. The data obtained allow us to recommend this technique of agriculture to reduce the share of net sources of carbon dioxide in the carbon balance.

1. Introduction
Estimation of carbon flows under different land use systems, including farming techniques, is of interest from the point of view of their impact on the global carbon cycle (sinks, reservoirs and sources) in the light of current climate changes [1, 2]. According to current concepts, agroecosystems are considered a carbon source, since a significant part of the primary production is alienated with the crop [3]. A high proportion of pure fallows in crop rotations contribute to the strengthening of uncompensated organic matter losses due to respiration of soil microflora, since there is no photosynthetic carbon sink. Reducing the share of net sources in carbon balance at the regional level is a requirement of the Framework Convention on Climate Change [1]. Replacing pure fallows with sidereal, where not only carbon is bound by plant biomass, but also its full return to the soil when tilled, is considered an effective method of regulating the processes of transformation of soil carbon [4]. It is important to consider the vegetation period of green manure crops, which is determined by their biological characteristics. For example, oilseed radish forms the biomass necessary for plowing in just 35-45 days. However, direct estimates of CO₂ emissions from the soil surface and carbon balance in general, when field crops with high growth rates are used as green manures, are rare [5]. It is also important to take into account the dependence of carbon transformation processes on specific soil and climatic conditions [6]. In this regard, the goal of our work was to study possible changes in the formation of carbon flows and balance during the green
manure of the fallow by short-term (35-40 days) sowing of oilseed radish in the forest-steppe of the Baikal region.

2. Objects and methods of research
The studies were carried out at the Agri-Ecological Station of the SIFIBR SB RAS located in the forest-steppe zone of the Irkutsk Region (53°33'58.75"N and 102°35'23.90"E). The climate of the region is sharply continental [7]. The amount of precipitation for the year ranges from 270-450 mm, with most of it (3/4) occurring during the warm period. Its duration is on average 102 days. The average monthly temperatures during this period range from 8.6 to 18.6 °C.

The soil of the experimental site is gray forest medium loamy (Greyic Phaeozems Albic [8]) with the following properties: bulk density 1.0-1.2; Corg 1.9-2.5%; N total 0.13-0.26%; pHKCl 5.8-6.0; amount of exchange bases 23.2-28.4 mg 100 g⁻¹.

Field experiments were performed during 2015-2017. Experience variants: 1 - pure fallow (control), 2 - fallow with short-term sowing of oil radish. The studies were carried out in four-field (2 rotation) and five-field (1 rotation) crop rotations; accordingly - experience I and experience II. The reference area in experience I was 1000 m², and in experience II - 80 m². Spring barley was the previous crop in all experiments. The exception was represented by 2015, where pure fallow was used in experiment II (the beginning of the field development). Due to the differences in rotations and forecrops, the Corg content in experiment I fluctuated within 2.5-2.8, and in experiment II 1.5-2.1%.

Oilseed radish (Raphanus sativus var. Oleifera Metzg) was used as a green manure crop in both crop rotations. Sowing was carried out in the second decade of June, when the conditions for temperature, light, and moisture were the most optimal for the rapid growth and accumulation of biomass plants. A 35-40 days later sowing, the biomass of oilseed radish was introduced into the soil using dump plowing to a depth of 22 cm. The method of cutting (0.25 m²) was used to take into account the aboveground biomass. At the same time, the underground biomass was estimated by selecting the roots from the soil monolith (10x10 cm). The daily of CO₂ emission from the soil surface was determined by the adsorption method [9]. The data were registered every 14 days from May to September. The total CO₂ emissions were calculated by linear interpolation for the entire observation season and its individual periods (before sowing a green manure crop, vegetation of oilseed radish and the period after plowing of green mass into the soil until the end of the warm season). The carbon balance was calculated as the difference between the net primary production of oilseed radish (NPP) and heterotrophic respiration of soil microflora (HR) [10, 11]. The magnitude of the HR was estimated on the basis of the total CO₂ emission for May-September, without taking into account the respiration of the roots. Root respiration was determined by the difference between CO₂ emissions from the soil with plants and from the fallow during the growing season (difference method). All measurements were performed in 4-5 replicates. The carbon content in soil and plant samples was determined by oxidation of organic matter by a mixture of H₂SO₄ and K₂Cr₂O₇ with titration using Mohr’s salt (Tiurin method).

Statistical data processing was performed using the SigmaPlot12.5 program. The Shapiro-Wilk test was used to assess the normality of the distribution. Since the distribution of data in terms of samples differed from the normal, for statistical processing we used the rank analysis of variance with the procedure of multiple comparisons (ANOVA on Rang; Tukey criterion). Mann-Whitney Rank Sum Test was used for comparison of the studied variants. The differences were taken statistically significant at p <0.05. The tables and figures show the median values, as well as the 25 and 75% percentile.

3. Results and discussion
Analysis of hydrothermic conditions in the years of research revealed their characteristics, which could have an impact on the biological activity of the soil and the vegetation of oilseed radish (figure 1). The total biologically active air temperatures > 10 °C (Tₐ) during the years of research significantly exceeded the “climatic normal” (1980–2090 C, with the normal of 1557 °C [7]). The amount of precipitation for the warm period, on the contrary, fluctuated within the limits of the “climatic normal” (229-267 and 257 mm, respectively). However, due to the uneven distribution of temperatures and precipitation during the
season, the moistening conditions of the territory of the experimental plot differed significantly in certain periods. According to Selyaninov’s Hydrothermic Coefficient (SHC), the beginning of the warm season in 2015 and 2017 was marked by a deficiency in moistening (0.8 and 0.8, versus 2.1 in 2016). Sowing oilseed radish (the second decade of May) in all years also coincided with moistening insufficient. The duration and intensity of the dry period decreased in a series of years: 2016 > 2015 > 2017. The period from August to September, when the green manure was introduced in the soil, was closest to the average long-term values in 2015. In 2016, excessive moistening was noted, and in 2017, on the contrary, insufficient. The differences in moistening during this period were mainly due to air temperatures. A sharp underperformance of heat was noted in 2017 (Ta = 382 ° C, versus 683 and 750 ° C in 2015 and 2016, respectively).

The total CO₂ emission from the soil surface for the warm season as a whole (May – September) in the variants with short-term green manure turned out to be significantly higher (1.3–1.6 times; p <0.05) than in the pure fallow (table 1). At the same time, the data of different years in experience I did not differ among themselves. For experience II, differences by year were found. In 2015, the CO₂ emission was significantly lower than in other years, which is due, apparently, to the difference in the previous culture. In this year, in connection with the start of development of the experimental field, the observation was carry out after fallow, and in other years - after spring barley. The data are in good agreement with the results presented in [12], where the magnitude of CO₂ emissions from the fallow closely correlated with the quantity of residues of the previous culture.

The increase in seasonal CO₂ fluxes from the soil surface was due to the growing season of the sidereal culture and the period after plowing green mass into the soil. Before sowing oilseed radish, the total CO₂ emissions for the studied variants in each of the experiences differed slightly, which confirms the relative alignment of the experimental plots and the correctness of the selected control. Higher rates in experience I compared with experience II are apparently due to a large carbon resource in soils.

Vegetation of oilseed radish helped to increase the total flow of CO₂ from the soil surface over this period (table 1). Indicators increased about 1.5 times compared to the control variant, regardless of experience and year of research. The exception was the 2016 data for experiment II, where the relative increase in the total CO₂ flux was 10%. Since the release of CO₂ from the soil with actively growing plants is associated mainly with respiration of the roots and rhizosphere microflora [13], this could be the result of a significant thinning of sowing against the background of a prolonged drought. Comparison of the results obtained simultaneously in the fallow and cropland, allowed us to estimate the proportion of root respiration and rhizosphere microflora in the total flux of CO₂ from the soil surface in the short-term cultivation of oilseed radish. The value of their joint contribution to the total CO₂ emissions during the growing season was 40-63%. Close estimates of the parameter (up to 50% of the total flux), obtained including isotope methods, are shown [13].

After plowing up the green mass of oilseed radish into the soil, the total CO₂ flux from its surface increased 1.4-2.3 times as compared with the control, and the differences in all years were statistically significant (p <0.05). Relative to pure fallow, the increase in experience I for the period amounted to 106, 108 and 38%, respectively in 2015, 2016 and 2017. In experience II, the increase in flux over the years reached 130, 48 and 50%. A smaller increase of values in the variants with the green manure of both experiences in 2017 was apparently associated with unfavorable hydrothermal conditions for
mineralization, especially temperature. As is known, the dependence of the rate of decomposition of organic matter on temperature is linear or exponential in nature [6, 14]. The low intensity of the mineralization processes in experience II under the conditions of 2016 could be due to the lower inflow of plant biomass in the soil due to sparse sowing. During the period of high availability of organic matter of plant origin, the contribution of soil organic matter to the outflow of CO$_2$ is insignificant [15].

**Table 1.** The total CO$_2$ emission from the surface of gray forest soil in the field experiences.

| Variant | Year | On the whole for the season (May – Sept) | In the periods of observation before green manure planting | during green manure vegetation | after plowing green mass |
|---------|------|------------------------------------------|------------------------------------------------------------|--------------------------------|--------------------------|
|         |      |                                          | Experience I                                               |                                |                          |
| 1       | 2015 | 210 [194;230]                            | 83 [75; 93]                                                | 81 [72;84]                     | 49 [38; 61]              |
|         | 2016 | 201 [192; 219]                           | 89 [82; 98]                                                | 70 [63; 73]                     | 46 [35; 57]              |
|         | 2017 | 166 [154; 204]                           | 52 [47; 76]                                                | 81 [74; 85]                     | 52 [50; 53]              |
| 2       | 2015 | 301 [277;328]**                         | 70 [68; 76]                                                | 124 [117; 149]**               | 102 [87; 112]**         |
|         | 2016 | 266 [251; 301]**                         | 64 [58; 76]                                                | 108 [102; 130]**               | 95 [80; 104]**          |
|         | 2017 | 272 [247; 278]**                         | 56 [49; 57]                                                | 130 [109; 137]**               | 72 [70; 75]**           |
|         |      |                                          |                                                            |                                |                          |
|         |      |                                          | Experience II                                              |                                |                          |
| 1       | 2015 | 91 [79;105]*                            | 20 [18; 24]                                                | 42 [35; 49]                     | 29 [25; 31]*            |
|         | 2016 | 173 [157; 182]                           | 43 [42; 46]                                                | 77 [69; 85]                     | 52 [43;54]              |
|         | 2017 | 129 [127; 142]                           | 44 [41; 54]                                                | 46 [40; 50]                     | 42 [40; 44]             |
| 2       | 2015 | 143 [129; 156]**/*/*/*                   | 21 [20; 24]                                                | 59 [45; 65]                     | 67 [56; 79]**           |
|         | 2016 | 214 [184; 231]**                         | 46 [42; 50]                                                | 85 [83; 101]**                  | 77 [72; 95]**           |
|         | 2017 | 175 [164; 190]**                         | 32 [32; 36]                                                | 75 [75; 87]**                   | 63 [60; 64]**           |

Note: 1 – pure fallow; 2 – fallow with short-term sowing of oilseed radish.
* statistically valuable (p<0.05) differences in years;
** statistically valuable (p<0.05) differences between variants.

Accounting for oilseed radish yielded estimated the amount of plant matter formed by its aboveground and underground biomass for a short period of cultivation (~ 40 days) in the conditions of the forest-steppe of the Baikal region. The total biomass ranged from 170 to 705 g dry matter m$^{-2}$ (figure 2). Regardless of experience, the maximum yield of green manure crops was obtained in 2017, and the minimum - in 2016, which corresponds to the severity of the aridity period during the growing season of these years. The initial fertility of the soil had no less influence on the formation of productivity. So, in experiences I, where its level was higher, the yield of oilseed radish in all years was higher. The ratio of the above-ground mass / roots (6.7-9.6) indicates that in all years the flow of organic matter into the soil was provided by the green mass.

**Figure 2.** Aboveground (1) and underground (2) oilseed radish mass in field experiences, g dry matter m$^{-2}$ (n=4).

Due to the unequal productivity of oilseed radish in experiences, the parameters of net primary production (NPP) varied widely (81-197 g C m$^{-2}$). In half the cases, the photosynthetic carbon sink did not compensate for its loss due to respiration of heterotrophic microflora (figure 3). As a result, a negative carbon balance was formed. The largest deficit (~128 g C m$^{-2}$) differed in the variant of fallow with short-term sowing of oilseed radish in experiences II under the conditions of 2016, when its productivity...
was low, and the loss of carbon due to the active mineralization of green mass and barley plant residues was significantly higher. High yields of green manure culture in the experiences of 2017, combined with unfavourable conditions for the mineralization of newly introduced organic matter, contributed to the formation of a positive carbon balance (+64 - +166 g C m⁻²). Also positive (+26 g C m⁻²) turned out to be a balance in the variant with the green manure of experience II in 2015, when the crop rotation field was located after the fallow. The reason could be a smaller stock and activity of the microbial pool in the absence of plant residues of the previous culture [16].

The carbon balance in the pure fallow, as is characteristic of this farming technique, was characterized by a significant deficit (-91 - -210 g C m⁻²). Its value was influenced by the soil carbon resource and the pool of plant residues of the previous culture, which is confirmed by the data in literature [10, 12]. Short-term green manure of the fallow reduced the deficit, and when combined conditions that are favorable for plant growth, but unfavorable for the mineralization of their green mass, contributed to the formation of a positive carbon balance. The important role of green manure in carbon sequestration and replenishment of its reserves in soils in the semi-arid climate of even tropical regions is shown in [4].

![Figure 3. Carbon balance in field experiences with different types of fallowing gray forest soil, g dry matter m⁻²: 1 - NPP of oilseed radiish; 2 - losses due to heterotrophic respiration of microorganisms; 3 - carbon balance. Variants: I - pure fallow; II - fallow with short-term sowing of oilseed radiish.](image)

4. Conclusion
Thus, the short-term green manure of the fallow in the conditions of the forest-steppe zone of the Baikal region contributes to a significant change in carbon fluxes in the agroecosystem, not only by increasing its gaseous losses, but also by intensive accumulation of phytomass. Short-term cultivation of oilseed radish due to rapid growth can be considered an effective farming technique, since it reduces and/or completely compensates for the deficit in the carbon balance in comparison with pure fallow.

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