Soil organic carbon losses from seasonally-frozen soils of agricultural ecosystems in West Siberia for the 20th century

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1. INTRODUCTION AND BACKGROUND

Soil organic matter (SOM) is one of the major soil components for ecosystems to properly function. Carbon makes up 56% of SOM. The reserve of organic carbon in soils world-wide totals 1500×10^9 tons. Soil cover of Siberia makes up 7.3% of the total soil cover, while soil organic carbon (SOC) reserve of Siberia amounts to 13.1%. Transfer of virgin ecosystems into agricultural ones is accompanied by the dramatic decrease of SOC contents and results in significant increase of emission of the most important greenhouse gas - CO_2. The SOC content decrease is preconditioned by about 5 times less input of plant debris and exudates into soil, changes in their quality, and higher mineralization rate of SOM, which is closely connected with tillage manner. Other factors such as fertilizing, irrigation, liming though are of certain significance, however their role is not that essential. Transfer of virgin ecosystems into hayfields and pastures is also accompanied by the decrease of SOC reserve due to permanent removal of phytomass and nutrients. However, these changes influence on organic carbon contents in soils to a lesser extent in comparison with arable ones.

Attempts to estimate the amount of SOC losses from big areas are associated with a number of difficulties; among them is the lack or total absence of SOC data in virgin ecosystems just before their transfer into agricultural ones. However, accuracy of estimation is of great significance as it helps to clarify the reasons of increase of atmosphere CO_2 concentration in the past and at the same time is a basis for the forecast of SOM changes in the future.

The great increase of agricultural land (more than 5 times) took place in West Siberia within the 20th century. Only in the middle of the 50-s about 50% of the actual arable lands were newly ploughed. At present, agricultural land reached its reasonable maximum. Just for comparison the area of arable land in the world increased to 2.5 times from 1860 to 1970, while in West Siberia almost 9 times. Therefore, ploughing of earlier untouched lands in West Siberia should no doubt have an essential impact on the increase of CO_2 concentration in atmosphere in the 20th century.

It should be noted that the only forest steppe and steppe zones include big areas of arable lands – 42 and 47% of the total zonal area, respectively. Hayfields and pastures occupy 29% and 36% of the total zonal area in forest steppe and steppe, respectively. Area of agricultural land in more north ecozones (taiga, forest tundra and tundra) of Western Siberia is negligible. Even southern taiga subzone includes only 3% of arable land and 4% of hayfields and pastures in sum.

The fact of significant decline of organic carbon contents in agricultural soils of Siberia was established quite a long time ago. One of the applied approaches was an estimation of organic carbon losses in arable soils as compared to nearby located virgin or old idle plots (Kotelnikov, 1966; Bogdanov, 1976; Leshkov and Leshkova, 1977; Gadjiev and Djukarev, 1984; Mishenko et al., 1985). The level of those losses is fairly different for different soils and makes up on the

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average 15% (Table 1). Of course, it is very rough estimation. However, as it was mentioned before, determination of real amounts of SOC losses are of high importance.

Table 1. Relative SOC losses in arable lands (0-20 cm) of West Siberia as compared to SOC contents in nearby virgin lands.

Soil type	*n*	SOC loss, %
Grey forest soils	3	11
Leached chernozem soils	5	13
Podzolized chernozem soils	1	32
Ordinary chernozem soils	9	12
Southern chernozem soils	3	23
Meadow-chernozemic soils	3	15
In average	24	15

Note. Soil names in the table and mentioned below are given as according to Russian Soil Classification.

At the beginning of 90-s A.A. Titljanova together with her co-workers made an attempt to assess the amount of SOC losses from arable soils of West Siberia (Titlyanova et al., 1995, 1998). It was based on organic carbon contents in soil samples taken from 710 profiles for the period from 1912 to 1992. These data were put in "Organic Carbon" database and calculated SOC losses as follows: [SOC contents in 1912-1930] – [SOC contents in 1980-1992]. But they used not well-grounded assumption that SOC reserve in soils had not changed till 1930 in comparison with virgin soils. Another significant drawback of this approach is great spatial variability of SOC distribution even within one and the same soil type.

2. MATERIALS AND METHODS

We applied another approach to estimation of SOC losses in case of anthropogenic soil transformation that was based on the results of soil examination of the former Altai region carried out by Moscow soil scientists in 1894 (Vydrin and Rostovskii, 1899). At present the former Altai region covers several administrative territories where the major part of the forest steppe zone of West Siberia is located. The participants of the 1894 expedition described more than 1000 soil profiles. SOC contents were determined by the Gustavson's method in about 35% of the total number of samples taken from the upper 20 cm layer. In the explanatory note to the map there was given a brief description of the sites of soil sampling with indication of the kind of land use (virgin land, arable one and so on).

In 1998 we searched for those sampling sites, that were located in the forest steppe zone mainly and those, which in 1894 were taken from virgin lands. All in all soil samples from 65 sites were taken. Among them 41 sites were located on arable lands, 9 - on hayfields, 7 - on pastures, and 4 - on virgin lands at present time. Besides 18 planned sites were excluded for different reasons: 14 ones – right before soil sampling due to doubtful description of each site (it was not surely clear that we had found site described by I.P. Vydrin and Z.I. Rostovskii in 1894) and 4 ones - after SOC analyses were carried out.

Three mixed samples from the upper 20 cm layer were taken from each site. Each mixed sample was comprised of 40 separate ones. Those plots, where mixed samples were collected, were in the distance of 70 m from each other. Undisturbed soil probes from every plot were also taken to measure soil bulk density. Standard method developed by I.V. Tjurin and applied in Russia at present was used to analyze SOC in soil samples (Belchikova, 1975).

3. RESULTS AND DISCUSSION

The results of SOC determination obtained by Gustavson's method in 1894 were converted to SOC contents measured by Tjurin's method. Taking into account soil bulk density at present and relation between bulk density of virgin and agricultural soils, the reserves of SOC were calculated in both 1894 and 1998. Earlier obtained data allow suggesting that though amounts of absolute SOC losses for various soils can differ significantly, however, relative losses given in percentage of the initial SOC contents are more leveled off in various soils. Therefore, we calculated SOC losses for all soil types of forest steppe zone together without subdivision by separate soil types. But 4 different kinds of land use (arable lands, hayfields, pastures, and virgin lands) were taken into account separately.

The obtained data were processed by 2 factors ANOVA program. As a result the SOC decreased on the average by 44% in arable lands, by 32% in hayfields and by 23% - in pastures for the period of 104 years (Table 2). No significant changes of SOC contents were detected in virgin lands. The differences between all average values obtained were valid on 1% level of significance. It is worth noting that the extent of effect of "type of land use" factor made up 62%, and of "field replication" factor - 0%. Average variation coefficient of SOC contents by field replication equaled approximately 7%.

Table 2. ANOVA analysis of average factor values of relative SOC losses in agricultural ecosystems of West Siberia expressed in % of initial SOC contents in 0-30cm soil layer.

Factor A (kind of agricultural use)	Factor B (field replication)			Average for factor A
	1	2	3	
Arable lands	44.2	44.7	43.9	44.2 d
Hayfields	30.7	32.3	32.0	31.7 c
Pastures	21.0	25.4	22.3	22.9 b
Virgin lands	1.5	0.3	6.8	2.8 a
Average for factor B	36.7 a	37.7 a	37.2 a	

Table 3. Up-to-date SOC contents (0-30 cm soil layer) in agricultural ecosystems of West Siberia, kg/m^2.

Soil groups	Gamzikov (1981)		Titlyanova, Naumov (1995)		Titlyanova et al. (1998)		SOC on average
	years	SOC	years	SOC	years	SOC	
Grey forest soils	1970-1980	8.8	1980-1990	10.0	1990-1995	8.9	9.2
Chernozems	1970-1980	12.5	1980-1990	12.0	1990-1995	11.8	12.1
Meadow-chernozemic soils	1970-1980	11.5	1970-1990	11.5	1990-1995	11.5	11.5
Solonetz and Solonchaks	1970-1980	10.4	-	-	1990-1995	8.2	9.3

The present amount of SOC reserve in agricultural ecosystems of West Siberia was calculated as average value according to 3 published sources obtained mainly from database “Organic Carbon” (A.A. Titlyanova with co-workers) and also by survey done by G.P.

Gamizkov (Table 3). It seems that difference between these values is caused less time period of soil sampling but much more the amount of soil samples included in the extracts.

The total area of West Siberian forest steppe zone, which made up more than 27 million ha, as well as the area of main soil types for various kinds of agricultural land were estimated on the base of charting materials. Soil types were classified in 5 groups with similar properties: the 1st one – different subtypes of grey forest soils, the 2nd one - different subtypes of chernozem soils, the 3rd one – different subtypes of semihydromorphic soils such as meadow-chernozemic soils, the next group – salted soils: solonchak and solonetz, and the 5th group – hydromorphic soils: meadow soils, solod soils and alluvial soils (Table 4). Later on, on the basis of estimated relative SOC losses for 3 kinds of agricultural land there were calculated the SOC losses from various soil types. The major losses of organic C from arable lands occurred in chernozem (60%) and meadow-chernozemic soils (23%) and from hay and pasture lands - in solonetz and solonchak soils (43%) and in meadow-chernozemic soils (35%). This distribution is justified by the structure of soil reserve in various kinds of agricultural lands, by SOC contents in different soil types, and by relative amounts of SOC losses caused by various kinds of agricultural use.

Table 4. Areas and SOC losses from soils of West Siberian forest steppe due to agricultural use during the 20th century.

Item	Soil group	Agricultural lands			Sum total / on average
		arable lands	hayfields	pastures	
Area of different kinds of agricultural lands, n × 10^3 ha	in all	11151	4169	4399	19719
Area of different kinds of agricultural lands, % of total area of forest steppe zone	in all	40.3	15.1	15.9	71.3
Relative SOC losses from upper 30 cm soil layer, % of initial SOC contents	for all soils	44.2	31.7	22.9	
SOC losses from upper 30 cm layer, % of total losses inside one kind of agricultural land	GF	9	5	5	8
	Ch	60	6	6	46
	MCh	23	35	35	26
	Sol	8	43	43	17
	Hyd	1	11	11	3

Note. GF – grey forest soils, Ch – chernozem soils, MCh – meadow-chernozemic (semihydromorphic) soils, Sol – solonchak and solonetz, Hyd – hydromorphic soils.

The SOC losses for 5 soil groups and for 3 kinds of agricultural use were calculated. Summarizing these values for 5 soil groups, the total SOC losses were estimated (Table 5).

Table 5. SOC losses from upper 30 cm layer in West Siberian forest steppe, n × 10^6 ton.

Soil group	Agricultural lands			
	arable lands	hayfields	pastures	sum total
GF	93	10	7	110
Ch	600	13	9	621
MCh	229	69	47	346
Sol	77	86	58	222
Hyd	5	21	14	40

It made up about 10×10^8 ton from arable lands, and 2×10^8 and 1.4×10^8 ton from hayfields and pastures, respectively. The overall SOC losses from soils of forest steppe zone for the 20th century made up 13.4×10^8 ton. At the Fig. 1 you can also see the change of areas of agricultural lands for the 20th century.

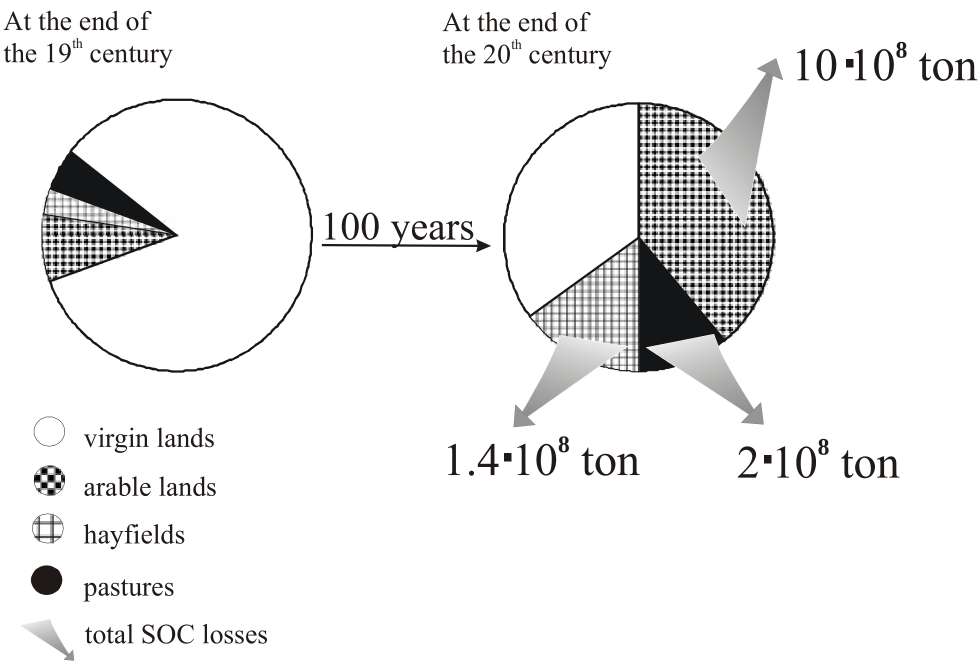

Fig. 1. Changes of land structure and total SOC losses from agricultural ecosystems of West Siberian forest steppe zone during the 20th century.

It has been established that it takes from 40 to 100 years for SOC content to get stabilized after onset of agricultural using, while for major types of soils – 50 years and that SOC decrease is of exponential character as the time goes (Stevenson, 1982; Stevenson and Cole, 1999; our unpublished data). Thus, taking into account that SOC content stabilization occurs on the new level within 50 years, the average rate of SOC losses from agricultural ecosystems of West Siberian forest steppe zone varies from 180 g/m^2 in arable lands to 96 g/m^2 in hayfields and to 61 g/m^2 in pastures in a year (Table 6).

Table 6. Average rates of SOC losses from agricultural ecosystems of West Siberian forest steppe for 50 years, g/m^2 per year.

Soil group	Agricultural lands			
	Arable lands	Hayfields	Pastures	On average
GF	146	85	55	124
Ch	192	112	72	185
MCh	182	107	68	133
Sol	147	86	55	86
Hyd	182	107	68	93
On average	180	96	61	136

The obtained data are 55% more, than the earlier presented data for West Siberian arable lands and is within the range for arable lands world-wide (Table 7). The SOC losses in hayfields come close to the upper level in all soils of the world.

Table 7. Comparison of SOC loss rates from different soils.

Soils cover	SOC loss rates, g/m^2 per year
All soils in the world, range	6-56
Arable soils in the world, range	53-493
All soils of West Siberia, on average	9
Arable soils of West Siberia, on average (Titlyanova et al., 1995)	116
Arable soils of West Siberia, on average (our data)	180

Our data on the relative SOC losses in arable lands are very close to the data, roughly estimated by Schlesinger and Buringh for worldwide soil cover (Table 8). Our data for hay and pasture lands are also similar to data of Buringh.

Table 8. Relative SOC losses (% of initial SOC contents) from agricultural lands of different kinds of using: our data and the data obtained by other researchers.

Soil cover	Relative SOC losses	Author
Arable lands, average for worldwide soil cover	40%	Schlesinger (1984)
Arable lands (after forest ecosystems), average for worldwide soil cover	48%	Buringh (1984)
Arable lands, West Siberia	44%	our data
Hayfields and pastures (after forest ecosystems), average for worldwide soil cover	28%	Buringh (1984)
Hayfields, West Siberia	32%	our data
Pastures, West Siberia	23%	our data

4. CONCLUSIONS

The presented research and calculations, based on the results of SOC determination in 1894 and on the database "Organic Carbon" enabled to estimate the SOC losses in agricultural lands of West Siberian for the period of the 20th century. Relative SOC losses (calculated as % of initial SOC contents) were equal 44% for arable soils, 32% for hayfields and 23% for pastures. The overall SOC losses from agricultural ecosystems of West Siberian forest steppe amounted to 13.4×10^8 ton. It's necessary to note that the relative SOC losses in hayfields and pastures were estimated for the first time for West Siberia, and as for arable lands the obtained data are 55% higher than the previously presented figures.

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