Promising agricultural technologies for growing winter wheat for sustainable agricultural development

A V Zelenev, O G Chamurliev, I V Krivtsov, A A Kholod, A N Sidorov and E S Vorontsova

Volgograd State Agrarian University, 26 University Avenue, Volgograd, 400002, Russia

E-mail: Zelenev.A@bk.ru

Abstract. In the arid zone of light chestnut soils of the Lower Volga region, in order to increase the influx of organic matter and basic nutrients into the soil, winter rye and yellow two-year-old clover should be cultivated in occupied fallows as sideral crops. To increase the replenishment of potassium in the soil, it is also recommended to grow phacelia on siderate as a fallow crop. Plowing oats in the form of green fertilizer led to a decrease in the input of organic matter and mineral nutrition elements into the soil compared to the control. The highest content of nitrate nitrogen, mobile phosphorus and exchangeable potassium in the arable layer of the soil during the sowing of winter wheat, when its plants leave for winter and spring regrowth, as well as during harvesting, was provided by the predecessors of the occupied fallows by winter rye, two-year-old clover and phacelia for siderate. The highest yield of winter wheat was obtained by the predecessors the pure fallow and occupied fallows by winter rye, sweet clover and phacelia for siderate. According to the predecessors, the occupied fallows by spring ginger and oats for siderate showed a significant decrease in the yield of winter wheat.

1. Introduction

The preservation and improvement of the fertility of zonal soils is the main problem of modern agriculture. The return of matter and energy back to the soil, instead of crops alienated with harvests, acquires an important role in the system of reproduction of soil fertility. The decrease in the main indicators of soil fertility and field crop yields occurs against the background of intensive use of arable land, a decrease in the share of perennial grasses in the structure of sown areas, a reduction in the use of mineral and, most importantly, organic fertilizers [1, 2, 3, 4].

Siderates are one of the powerful biological resources that improve soil fertility and crop yields. Organic matter, which is obtained as a result of growing green fertilizers, is the main reserve of valuable nutrients for plants. When plowing into the arable soil layer, these substances turn into an easily digestible form for plants not immediately, but over time, during the entire growing season of the crop, ensuring constant plant growth [5, 6, 7].

The most qualitative selection of sideral crops is necessary to increase the efficiency of the use of the occupied fallows in field biologized crop rotations. The cultivated siderates must meet the following important requirements: have the lowest possible seeding rate to reduce the cost of buying seeds, a low transpiration coefficient in order to preserve and efficiently use the productive moisture in the soil, have
an accelerated growth of biological mass so that it can be plowed into the soil as early as possible, guarantee high yields with a better quality composition [8, 9, 10].

In the arid conditions of light chestnut soils of the Lower Volga region, very little research on the selection, cultivation technology, use of green fertilizers, their effect on the diet and yield of winter wheat has been conducted. This was the reason for the generalization of the obtained research results, which contributed to the scientific confirmation of the use of the occupied fallows and the sideral crops cultivated in them as predecessors of winter wheat and the main biological factor in increasing soil fertility in the Lower Volga region.

2. Materials and methods

Studies on the effectiveness of the occupied fallows and sideral crops grown in them in improving nutrition and stabilizing the yield of winter wheat in field biologized crop rotations were carried out in 2013-2017 and 2017-2020 agricultural years in the dry-steppe zone of chestnut subzone of light chestnut soils of the Lower Volga region in the experimental field of the Federal State Budgetary Research Center of Agroecology and Complex Reclamation of the Russian Academy of Sciences.

The soil of the site is light chestnut medium-sized low-humus heavy loamy with a content of 1.74-2.0% humus in the arable 0-0.3 m layer, easily hydrolyzable nitrogen - 32-36 mg/kg, mobile phosphorus - 18-21 mg/kg and exchangeable potassium - 330-370 mg/kg of absolutely dry soil. The pH of the soil solution in the arable layer was 8.1. The cation exchange capacity was 25.7 mg·eq/100 g of soil.

Two stationary field experiments were laid. In experiment No. 1, the predecessors of winter wheat were: 1) pure fallow (control); 2) occupied fallow (winter rye for siderate); 3) occupied fallow (spring ginger for siderate). In experiment No. 2, the predecessors of winter wheat were: 1) pure fallow (control); 2) occupied fallow (two-year-old sweet clover for siderate); 3) occupied fallow (oats for siderate); 4) occupied fallow (phacelia for siderate).

Agricultural technology of winter wheat cultivation was generally accepted for the research area, except for the studied predecessors and methods of biologization. In experiment No. 1, sideral crops winter rye and spring ginger were sown in the spring. The basic tillage included chiseling at 0.30-0.32 m and turnover of the surface layer to a depth of 0.20-0.22 m with the OCHO-5-40 tool with multifunctional working bodies of the "RANCHO" modular type (blade and wide chisel). In experiment No. 2, the basic tillage was similar in experiment No. 1. Sideral crops, two-year-old sweet clover were sown under the cover of mustard, oats and phacelia by pure sowing in spring in the occupied fallow. In both experiments, in the first decade of June, winter rye in the tillering phase, spring ginger, phacelia and sweet clover in the budding phase, oats in the sweeping phase were crushed and embedded in the soil as a green fertilizer with a heavy disk harrow BDT-3 to a depth of 0.10-0.12 m. Winter wheat of the Kamyshtanka 5 variety was sown with a seeding rate of 3.0 million pieces of germinating seeds per 1 ha in the usual ordinary way with row spacing of 0.21 m with a grain seeder Don-114 to a depth of 0.05-0.07 m, which can work according to traditional, minimal and no tillage.

The variants in the experiment were placed in a randomized way in one tier with three repetitions. The area of the experimental plot was 900 m², the accounting area was 782 m². The mass of crop-root residues of sideral crops was taken into account by the method of monoliths according to Stankov in an eight-fold repetition after their harvesting. The wet and air-dry aboveground mass of sideral crops was determined by selecting sheaves from 0.25 m² sites in four-fold repetition and further weighing them in the laboratory. The content of nitrate nitrogen in the soil was determined by the Grandval-Lyaju method with the conversion of the content of nitrates NO₃ to nitrate nitrogen N-NO₃ using a conversion factor of 0.226. The content of mobile phosphorus and exchangeable potassium in the soil was determined by the Machigin method. The economic yield of winter wheat was determined by the weight method using a continuous combine harvesting of each plot. Then it was brought to the standard 14% humidity and 100% purity.

The amount of precipitation in 2013-2014, 2014-2015, 2015-2016, 2016-2017, 2017-2018, 2018-2019 and 2019-2020 agricultural years, respectively, were 435.5, 266.8, 554.8, 374.9, 391.0, 388.3 and 376.7 mm. The average annual precipitation was 339.7 mm.
3. Results and discussion

Previous studies have found that the cultivation and embedding of sideral crops on green fertilizer contributed to the compensation of part of traditional organic fertilizers and, in combination with nitrogen fixation of legumes, led to a reduction in the range of disruption of the organic matter and energy cycle in agrobiocenoses. Plowing 35-40 t/ha of green mass of siderates into the soil equated to 30-40 t of manure. When using sweet clover and phacelia for siderate, the soil received a total aboveground and crop-root absolutely dry mass, respectively, 5.9-9.5 and 6.7-8.8 t/ha, which is 1.8-2.4 times higher than that of oats, where this indicator was 2.8-4.9 t/ha [11, 12, 13]. In our experiments, the amount of aboveground and root air-dry mass of sideral crops that entered the arable soil layer was determined (Table 1).

Table 1. Aboveground and root air-dry mass of sideral crops in experiments, t/ha.

| Variant No. | Crop              | Air-dry mass       |
|-------------|-------------------|--------------------|
|             |                   | root   | aboveground | total  |
| Experience No. 1 (average for 2014-2017) |                   | 3.65   | 1.89        | 5.54   |
| 2           | Winter rye        | 1.00   | 1.14        | 2.14   |
| 3           | Spring ginger     | 0.74   | 1.17        | 1.91   |
| Experience No. 2 (average for 2017-2020) |                   | 0.53   | 1.07        | 1.60   |
| 2           | Two-year-old sweet clover | 0.62 | 1.09        | 1.71   |
| 3           | Oats              | 0.74   | 1.17        | 1.91   |
| 4           | Phacelia          | 0.53   | 1.07        | 1.60   |

Analysis of the Table 1 data shows that in experiment No. 1, the highest air-dry root and aboveground mass, which was plowed into the soil, was provided for winter rye for siderate, respectively, 3.65 and 1.89 t/ha, the lowest for spring ginger for siderate, respectively, 1.00 and 1.14 t/ha. As a result, the total air-dry mass entering the soil in winter rye was 5.54 t/ha, and in spring ginger was 2.14 t/ha, which was lower than in winter rye by 3.4 t/ha or 61.4%.

In experiment No. 2, the highest amount of organic matter with air-dry root and aboveground mass in the soil was supplied with two-year-old sweet clover siderate, respectively, 0.74 and 1.17 t/ha, with air-dry sideral mass of phacelia, respectively, 0.62 and 1.09 t/ha, and the lowest amount - with air-dry sideral mass of oats, respectively, 0.53 and 1.07 t/ha. The largest total air-dry mass of sideral crops was formed in two-year-old sweet clover - 1.91 t/ha, the smallest in oats - 1.60 t/ha, which was lower than in sweet clover by 0.31 t/ha or 16.2%. Phacelia for siderate formed more organic matter than oats by 0.11 t/ha or 6.9% and less than sweet clover by 0.2 t/ha or 10.5%.

Studies have found that the currently existing natural resources of the supply of nutrients to the soil did not compensate for their losses with the cultivated crop yield. Cultivated sideral crops, due to their unique root system, transformed the elements of the mineral nutrition of plants into an accessible form, and also, getting into the soil solution during the period of constant and long mineralization of organic matter, they did not accumulate in excessive amounts in the soil [14, 15, 16]. In our experiments, the regulation of nutrients was carried out due to the entry of organic matter into the soil in the form of a sideral mass (Table 2).

Analysis of the Table 2 data shows that in experiment No. 1, the highest balance of basic nutrients was provided as a result of plowing into the soil of the sideral air-dry root and aboveground mass of winter rye, respectively, nitrogen, phosphorus and potassium - +47.8, +12.6, +26.7 kg/ha and +42.9, +7.1, +23.1 kg/ha. From the root and aboveground air-dry sideral mass of spring ginger, nitrogen, phosphorus and potassium were supplied to the arable soil layer, respectively, +13.2, +3.8, +7.6 kg/ha and +26.0, +4.3, +13.3 kg/ha. The largest total number of basic nutrients coming from the root and aboveground air-dry sideral mass was observed in winter rye: nitrogen - +90.7 kg/ha, phosphorus - +19.7 kg/ha and potassium - +49.8 kg/ha, which was higher than in spring ginger, respectively, nitrogen by 51.5 kg/ha, phosphorus - 11.6 kg/ha and potassium - 28.9 kg/ha.
winter rye for siderate nitrate nitrogen in the arable soil layer was provided when winter wheat plants were left for winter by elements with organic matter of sideral crops is presented in Table 3. Monitoring of the dynamics of nitrogen and phosphorus was also provided in the root and aboveground air-dry mass of the sweet clover, respectively, +10.1, +2.0 kg/ha and +24.6, +6.2 kg/ha, potassium - in phacelia, respectively, +7.7 and +15.1 kg/ha. The highest total balance in nitrogen and phosphorus was also provided in the two-year-old sweet clover, respectively, +34.7 and +8.2 kg/ha, in potassium - in phacelia - +22.8 kg/ha. The lowest total balance of nutrients was provided in oats: nitrogen - +21.1 kg/ha, phosphorus - +4.6 kg/ha and potassium - +17.9 kg/ha.

In experiment No. 2, the highest positive balance of nitrogen and phosphorus was provided with the root and aboveground air-dry mass of the sweet clover, respectively, +10.1, +2.0 kg/ha and +24.6, +6.2 kg/ha, potassium - in phacelia, respectively, +7.7 and +15.1 kg/ha. The highest total balance in nitrogen and phosphorus was also provided in the two-year-old sweet clover, respectively, +34.7 and +8.2 kg/ha, in potassium - in phacelia - +22.8 kg/ha. The lowest total balance of nutrients was provided in oats: nitrogen - +21.1 kg/ha, phosphorus - +4.6 kg/ha and potassium - +17.9 kg/ha.

It was previously established that the most effective way to increase the reserves of basic nutrients in the soil was considered to be the entry of organic matter in the form of green fertilizers into the arable layer. Monitoring of the dynamics of the basic elements of nutrition is necessary both for understanding the processes that occur in the soil, but also for the implementation of practical measures aimed at improving nitrogen, phosphorus and potassium regimes in grain crops [17, 18, 19, 20]. The result of our studies confirming the dependence of the nutrient content in winter wheat crops on the incoming elements with organic matter of sideral crops is presented in Table 3.

### Table 2. Balance of basic nutrition elements with organic matter of sideral crops, kg/ha.

| Variant No. | Crop                     | Experience No. 1 (average for 2014-2017) | Experience No. 2 (average for 2017-2020) |
|-------------|--------------------------|------------------------------------------|------------------------------------------|
| 2           | Winter rye               | +47.8                                    | +10.1                                    |
| 3           | Spring ginger            | +13.2                                    | +1.9                                     |
| 2           | Two-year-old sweet clover| +10.1                                    | +2.0                                     |
| 3           | Oats                     | +5.0                                     | +1.6                                     |
| 4           | Phacelia                 | +9.0                                     | +1.9                                     |

In experiment No. 2, the highest positive balance of nitrogen and phosphorus was provided with the root and aboveground air-dry mass of the sweet clover, respectively, +10.1, +2.0 kg/ha and +24.6, +6.2 kg/ha, potassium - in phacelia, respectively, +7.7 and +15.1 kg/ha. The highest total balance in nitrogen and phosphorus was also provided in the two-year-old sweet clover, respectively, +34.7 and +8.2 kg/ha, in potassium - in phacelia - +22.8 kg/ha. The lowest total balance of nutrients was provided in oats: nitrogen - +21.1 kg/ha, phosphorus - +4.6 kg/ha and potassium - +17.9 kg/ha.

### Table 3. The content of basic nutrients in the arable soil layer in winter wheat crops, mg/kg of absolutely dry soil.

| Variant No. | Predecessor, biologization method | Sowing | Leave for winter | Spring regrowth | Harvesting |
|-------------|-----------------------------------|--------|-----------------|-----------------|------------|
| 1 (c)       | Pure fallow                       | 5.01   | 32.1            | 355.8           | 28.4       |
| 2           | Occupied fallow (winter rye)      | 7.26   | 41.8            | 385.2           | 9.21       |
| 3           | Occupied fallow (spring ginger)   | 6.39   | 31.1            | 366.2           | 8.55       |
| 1 (c)       | Pure fallow                       | 6.11   | 21.5            | 324.2           | 7.48       |
| 2           | Occupied fallow (sweet clover)    | 6.44   | 30.2            | 352.9           | 7.91       |
| 3           | Occupied fallow (oats)            | 6.28   | 26.9            | 338.5           | 7.84       |
| 4           | Occupied fallow (phacelia)        | 6.47   | 27.3            | 348.9           | 8.18       |

Analysis of the Table 3 data allows us to conclude that in experiment No. 1, the highest content of nitrate nitrogen in the arable soil layer was provided when winter wheat plants were left for winter by winter rye for siderate – 9.21 mg/kg, which is higher than in the control variant for pure fallow by 1.72...
mg/kg of soil or 23.0%. During this period, the content of nitrate nitrogen in the soil according to the predecessor the occupied fallow by spring ginger for siderate was 8.55 mg/kg, which was also higher than in the control by 1.06 mg/kg of soil or 14.1%. The content of nitrate nitrogen for the spring regrowth of winter wheat plants was slightly lower than when leaving for winter due to low temperatures, which affected the activity of the nitrification process. By sowing winter wheat, the highest content of nitrate nitrogen was provided in the arable soil layer according to the predecessor the occupied fallows by winter rye for siderate – 7.26 mg/kg of soil, which is higher than the control by 2.25 mg/kg or 44.9%. By harvesting winter wheat, the content of nitrate nitrogen in the soil was the lowest - 2.87-4.08 mg/kg of soil. It should be noted that the content of nitrate nitrogen in the arable soil layer less than 10 mg/kg of absolutely dry soil is considered very low according to Grandval-Lyaju.

The highest content of mobile phosphorus in the arable soil layer was provided when sowing winter wheat on the occupied fallow by winter rye for siderate - 41.8 mg/kg of soil, which is higher than the control by 9.7 mg/kg or 30.2%. The content of this element when sowing winter wheat on the occupied fallow of spring ginger for siderate decreased compared to the control variant by 1.0 mg/kg of soil or 3.1%. By the time winter wheat plants left and during spring regrowth, the content of mobile phosphorus in the arable soil layer decreased. During the harvesting of winter wheat, the phosphorus content in the soil for the occupied fallows was 29.9-30.6 mg/kg of soil, which was higher than the control variant, pure fallow, by 3.2-3.9 mg/kg or 12.0-14.6%. It should be noted that according to Machigin's classification, the content of mobile phosphorus in the arable layer from 31 to 45 mg/kg is considered increased, and from 15 to 30 mg/kg of absolutely dry soil is considered average.

The highest content of exchangeable potassium in the arable soil layer was provided during harvesting of winter wheat in the variant according to the predecessor the occupied fallow by winter rye for siderate – 445.3 mg/kg, which is higher than in the control for pure fallow by 48.9 mg/kg of soil or 12.3%. For the occupied fallow of spring ginger for siderate, the content of this element in the harvesting was higher than in the control by 23.2 mg/kg of soil or 5.8%. Also, a high content of exchangeable potassium in the arable layer was noted during the spring regrowth of winter wheat plants – 414.8 mg/kg of soil, which is 59.3 mg/kg or 16.7% higher than the control variant. In other variants, when sowing winter wheat, leaving for winter and spring regrowth of its plants in the control and according to the occupied fallow of spring ginger for siderate, the content of exchangeable potassium in the arable layer was provided by Machigin at an elevated level - from 301 to 400 mg/kg of absolutely dry soil.

In experiment No. 2, the highest content of nitrate nitrogen in the arable layer was provided during the spring regrowth of winter wheat on the occupied fallow by phacelia for siderate - 8.23 mg/kg of soil, which is higher than the control, the predecessor the pure fallow, by 0.74 mg/kg or 9.9%. Slightly lower content of this nutrient was noted in the same variant, but when winter wheat plants left for winter - 8.18 mg/kg of soil. According to the predecessor the occupied fallow by sweet clover for siderate, the content of nitrate nitrogen during the leaving for winter of winter wheat plants and spring regrowth was the same, and amounted to 7.91 mg/kg of soil. When sowing and harvesting of winter wheat, the content of nitrate nitrogen in the arable layer was also very low and, accordingly, on the occupied fallows equaled 6.28-6.47 and 5.37-5.70 mg/kg of absolutely dry soil.

The highest content of mobile phosphorus in the arable soil layer was provided during the harvesting and spring regrowth of winter wheat for the occupied fallow by sweet clover for siderate, respectively, 33.5 and 32.7 mg/kg of soil, which is higher than the control variant, the predecessor the pure fallow, by 2.7 and 5.6 mg/kg or 8.8 and 20.7%. Also, an increased content of mobile phosphorus was noted in the harvesting of winter wheat on the occupied fallow by oat and phacelia for siderate, pure fallow, respectively, 32.0, 31.0 and 30.8 mg/kg, and during the spring regrowth of plants on the predecessor the occupied fallow by oat for siderate - 30.6 mg/kg of absolutely dry soil. When sowing and leaving for winter of winter wheat, the content of mobile phosphorus was average and, respectively, equaled 6.11-6.47 mg/kg and 17.6-26.9 mg/kg of soil. The average content of this element was also noted during the spring regrowth of winter wheat plants on pure fallow and the occupied fallow by phacelia for siderate, respectively, 27.1 and 27.6 mg/kg of absolutely dry soil.
The highest increased content of exchangeable potassium in the arable layer of the soil was provided when sowing winter wheat according to the predecessor the occupied fallow by sweet clover for siderate - 352.9 mg/kg, which is higher than the control variant, the predecessor the pure fallow, by 28.7 mg/kg of soil or 8.8%. Variants with the occupied fallow by phacelia and oats for siderate also exceeded the control for the content of this element, respectively, by 24.7 and 14.3 mg/kg soil or 7.6 and 4.4%. When winter wheat plants leave for winter, spring regrowth and for harvesting, the best option was also the one where this crop was cultivated according to the occupied fallow by sweet clover for siderate. It should be noted that in terms of the content of exchangeable potassium in the arable layer, all variants corresponded to an increased level and only in the control variant, where the predecessor of winter wheat was pure fallow, the content of this element during spring regrowth and harvesting was average and, respectively, amounted to 299.2 and 292.3 mg/kg of absolutely dry soil.

Previous studies have established that sideral crops for fertilizer in the occupied fallows are an important biological factor in the reproduction of soil fertility and increasing the yield of grain crops in agrocenoses [21, 22, 23, 24, 25]. In our experiments, the yield of winter wheat depended on the input of organic matter into the soil in the form of root and aboveground air-dry mass of sideral crops (Table 4).

**Table 4.** Influence of predecessors and sideral crops on the yield of winter wheat in experiments, t/ha.

| Variant No. | Predecessor, biologization method | Yield Experience No. 1 (average for 2014-2017) | LSD05 0.05  
|-------------|-----------------------------------|-------------------------------------------------|---------  
| 1 (control) | Pure fallow                       | 2.69                                            |  
| 2           | Occupied fallow (winter rye)      | 2.68                                            |         
| 3           | Occupied fallow (spring ginger)   | 2.29                                            | 0.06     
|             | LSD05                             |                                                  |         
| 1 (control) | Pure fallow                       | 1.80                                            | 0.09     
| 2           | Occupied fallow (sweet clover)    | 1.80                                            |         
| 3           | Occupied fallow (oats)            | 1.68                                            |         
| 4           | Occupied fallow (phacelia)        | 1.78                                            |         

The analysis of the Table 4 data allows us to conclude that in experiment No. 1, the highest yield of winter wheat was obtained according to the predecessors the pure fallow (control) and the occupied fallow by winter rye for siderate, respectively, 2.69 and 2.68 t/ha. According to the predecessor the occupied fallow by spring ginger for siderate, the yield of winter wheat was significantly inferior to the control variant by 0.4 t/ha or 14.9%.

In experiment No. 2, the yield of winter wheat on predecessors the occupied fallows by sweet clover and phacelia for siderate was at the level with the control variant and amounted to 1.80 and 1.78 t/ha, respectively. In the control, this indicator was 1.80 t/ha. And only according to the predecessor on the occupied fallow by oats for siderate, the yield of winter wheat was significantly inferior to the control by 0.10 t/ha or 6.7%.

4. Conclusion
In arid conditions of light chestnut soils of the Lower Volga region, to improve the nutritional regime and stabilize the yield of winter wheat, it is necessary to grow this grain crop on the occupied fallow by winter rye, sweet clover and phacelia for siderate.

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