Development of Deep Placement Fertilizer Applicator for Grain Production in Russian Federation

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Abstract

Nowadays there is a gap between the equipment available in the Russian market and agricultural stakeholders' need for the equipment embracing modern technologies for grain cultivation. Therefore, the purpose of this study is to develop a resource-saving Deep Placement Fertilizer Applicator (DPFA) prototype for grain production in Russia.

To achieve the goal of the research, this study first determined the impact of different tillage systems on the grain yield and costs in the Republic of Buryatia, Russia. The minimum tillage and no-tillage systems present expedient alternatives to the conventional system of soil tillage, due to crop yield increase, cost reduction and to their conservation effects on the soil as compared to the conventional system. The minimum tillage method presupposes the use of subsoil and deep soil tillage devices, such as the chisel plow. Therefore, an advanced, resource-saving chisel plow for grain production in the Republic of Buryatia was developed. The proposed model reduced resistance of soil to the working parts and increased operational reliability of the device. Data of the equivalent stress, equivalent elastic strain, total deformation, and mass were obtained using the FEM to determine the optimum design of the chisel plow; these values for the optimized construction have decreased by 4.6, 2.1, 5, and 8% compared with the original design, respectively. Optimization of the chisel plow design was achieved by decreasing its mass and increasing its service life.

Finally, a resource-saving DPFA prototype with optimum design of chisel plow for grain production was developed. The characteristics of new DPFA prototype are Deep Placement fertilization, which is one of environmentally friendly farming method, and saving on labor costs because it simultaneously performs tillage, fertilization, and seeding.

Furthermore, top dressing application is not required because the effect of fertilizers is kept over a more extended period by the Deep Placement fertilization.

For the DFPA prototype fabrication, the idea, the 2D and 3D engineering drawings of the DPFA were submitted to the Project of development of high-speed seeder with DPFA for the large-scale Russian farming (Project). The Project has been realized between Niigata University and Primorskaya State Academy of Agriculture from November 1, 2017. The fabrication of the proposed chisel plow was made during the first stage of the Project.

Chapter 1 Introduction

"One of the most important issues of the twenty-first century is the production of a sufficient amount of food for the population and, at the same time, environmental protection."

Nobel Prize Laureate, Dr. Norman Borlaug.

The Russian Federation is one of the largest grain producing and processing regions in the world, and it possesses 20% of the world's supply of fertile land. According to the Food and Agriculture Organization of the United Nations, Russia could potentially feed two billion people. However, the post-reform period appeared to be an ordeal for almost all sectors of the Russian economy, particularly for agriculture. It has to be acknowledged that Russia failed to achieve the pre-reform level of agricultural development and fully restore its production capacity (Kalabekov, 2010).

Economic conditions dictate the need for a transition to new resource-saving technologies for crop cultivation. Scientific developments and production experience allow proposing new technologies for grain production based on technological method optimization. The basis of low-cost machine technology is a powerful energy tool, methods of minimum tillage, optimal, rational methods of introducing mineral fertilizers and plant protection products. Technological operations should be energy-saving, environmentally friendly and low-cost. They do not reduce the soil fertility; provide a yield with a high level of production profitability. Nowadays there is a gap between the equipment available in the Russian market and agricultural stakeholders' need for the equipment embracing modern technologies for grain cultivation. Therefore, the purpose of this study is to develop a resource-saving Deep Placement Fertilizer Applicator prototype for grain production in the Russian Federation. Following methodologies were adopted to achieve the goal of the research. The purpose of Chapter 2 is to determine the impact of different tillage systems on the grain yield and costs. The most promising soil protective, resource-saving technology currently in the Republic is minimum tillage. The minimum tillage method presupposes use of subsoil and deep soil tillage devices, such as the chisel plow. In farming, chisel plows are designed for subsoil tillage of compacted soil layers that prevent natural air and water exchange. Therefore, the purpose of Chapter 3 is to develop an advanced, resource-saving chisel plow for grain production in the Siberian region, which includes the Republic of Buryatia. Finally, the purpose of Chapter 4 is to develop a resource-saving Deep Placement Fertilizer Applicator prototype for grain production in Russia.

Chapter 2

Effects of tillage systems on grain production in the Republic of Buryatia, Russia

2.1 Introduction

Grain production is one of the main agricultural sectors in the Republic of Buryatia, Russia. Severe climatic conditions, specific landscape traits, and soil diversity are among the causes of unsustainable grain production in the Republic (Bolonev, 2001). The total sown area is 152 600 ha, with grain and leguminous crops occupying about 56% of this total. Wheat represents the most significant share of grain crops, accounting for over 52.7%, followed by oats and barley (Federal State Statistic Service, 2016).

The main types of soils in the arable land of Buryatia are chestnut soil (43.2%), gray forest soil (22.5%), and black earth (12.3%) (Batudaev et al., 2010). The conventional moldboard cultivation technology, which involves multiple passes of tractors and machines in the field, was implemented in the Republic during the Soviet period. Theoretical and technological recommendations for farming that did not consider local specifics were developed in the central regions of the USSR. As a result, problems of soil compaction and fertility preservation of arable land have arisen and become more acute every year (Batudaev et al., 2010).

The following critical problems of grain production have to be addressed: (1) Cultivated crop yields must be increased; (2) Costs must be reduced and crop production profitability increased; and (3) Soil fertility must be restored and improved. The key to solving these problems requires involvement of all technologies toward resource saving, based on Russian and world experience (Revyakin et al., 2011).

Sustainable agriculture should be organized into a system and analyzed as a relationship: soil–plant–climate area–socioeconomic conditions–crop efficiency (Wang et al., 2008; Bucur et al., 2011; Afzalinia et al., 2012; Domuta et al., 2012). Multifunctional technologies aim to reduce resource consumption, particularly in the area of aggressive soil tillage, while simultaneously obtaining high yields, soil conservation, and environmental protection (Ailincai et al., 2011; Marin et al., 2011; Gao et al., 2012). The influence of soil tillage systems on soil properties and resource efficiency is shown by the important effects they have on conservation of soil fertility and the sustainability of agricultural systems (Uhlin, 1998; Sarauskis et al., 2009; Vural and Efecan, 2012).

Currently, the most promising soil-protecting, resource-saving methods include minimum tillage and no-tillage. Minimum tillage and no-tillage aim for maximum accumulation and conservation of moisture in the soil, reduction of machinery passes over the field, and reduction in total costs for grain production (Rusu, 2014; Sandakov et al., 2019 in press).

The most evident effect of tillage is documented for soil organic matter. Reicosky (2001) reports that under comparable rotation there is a gradual increase in soil organic matter under minimum tillage regimes. The highest humus content is found in no-tillage and the lowest in plowing systems. Moreover, the distribution pattern of organic matter in the soil profile matches very closely the concentration of soil biota, showing high levels in the topsoil and declining with depth. Carbon enrichment of unplowed soils indicates that the conservation of soil organic matter contributes to carbon sequestration and lower global warming impacts (Reicosky, 2001). Domestic studies on the use of resource-saving technologies also affirm humus increase in the soil (Panov et al., 2008).

Over the last decade, several studies (Larionova et al., 2003; Romanovskaya, 2008; Vuichard et al., 2008; Kurganova et al., 2010, 2014; Schierhorn et al., 2013) aimed to estimate the total carbon sequestered in Russian soils due to the croplands abandonment. However, such estimations were not performed for the croplands of the Republic of Buryatia, leaving this important research topic unexamined. Nor has there been sufficient past research, or scientific results, in the area of soil compaction mitigation and its evaluation from the standpoint of yield and costs in Buryatia. This chapter, therefore, aims to add to the robust experiment-based knowledge that does exist and to determine the impact of different tillage systems on grain yield and costs in Buryatia.

2.2 Material and Methods

2.2.1 Study site

Experimental work was carried out on Kolkhoz Iskra farm near Ulan-Ude (51°8′11.4828″N, 108°14′14.2908″E), the Mukhorshibirsky region in the Republic of Buryatia, Russia, in 2013–2015.

Figure 1. Map of the study site

To test the efficiency of minimum tillage compared with conventional tillage, a production experiment according to the following conditions was carried out:

A: Conventional. Moldboard plowing - K-701, PLN 8-40. Separate seeding with SZU-3.6.

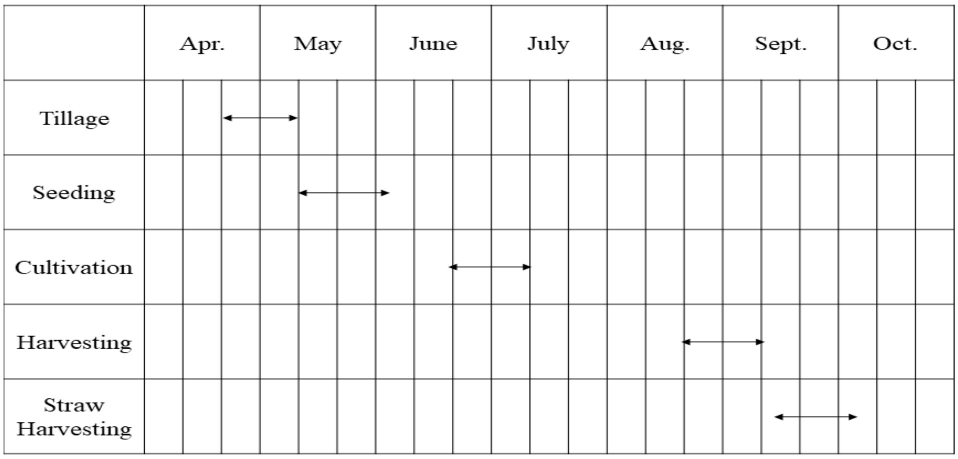
B: Resource saving. Cultivation with APD-7.2. Separate seeding with SZU-3.6.

C: Resource saving. Cultivation with APD-7.2. Seeding with Kuzbass-8.5.

D: Resource saving. Simultaneously cultivating and seeding with Kuzbass-8.5.

The oats variety was *Dogoi*, the seeding rate was 4.5 million pcs grains per ha, and the sowing date was 27 May. Crop care and harvesting were the same in all variants of the experiment (Table 1).

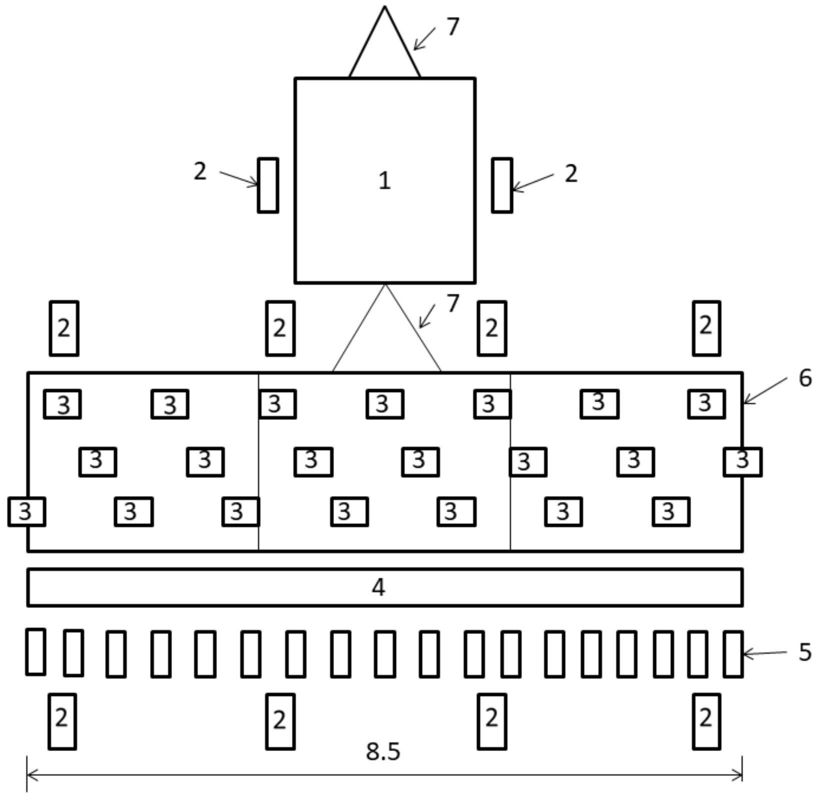
Table 1. Oats production calendar in Buryatia



2.2.2 Seedling complex Kuzbass-8.5

A comparative test of wheat seeding with Kuzbass-8.5 on 1000 ha was also carried out. Calculations of the costs per hectare of arable land for various agro-technical works were made while comparing conventional and minimum tillage.

The seeding complex Kuzbass-8.5 (Figure 2) performs multiple operations in one pass: cultivating, harrowing, seeding, applying fertilizers, packing and leveling the soil. Use of this complex allows the gap between soil preparation and seeding, which is typical in conventional technology in Russia, to be eliminated. Favorable conditions are created for germination and the formation of a normally developed plant in the future (Agro LLC, 2018).



unit: m

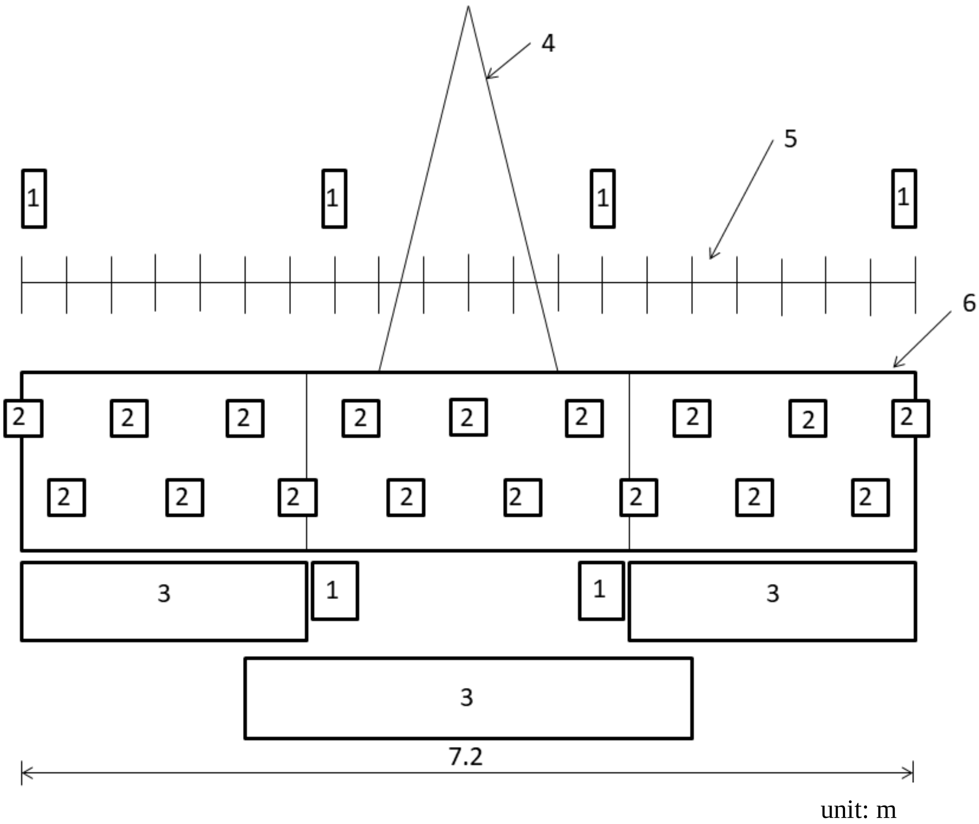
1: tank of seed and fertilizer, 2: wheel, 3: furrow-opener, 4: harrow,

5: soil packer, 6: frame, 7: hitch attachment.

Figure 2. Schematic diagram of Kuzbass-8.5

2.2.3 Tillage unit APD-7.2

The design of the tillage unit APD-7.2 (Figure 3) means that damp soil is not extracted from the lower layers, so retaining moisture; soil cultivation is carried out at a given depth; and the use of this implement allows the saving of energy resources, as several soil tillage operations are performed in one pass (Sibselmash OJSC, 2018).



1: wheel, 2: chisel, 3: rollers, 4: hitch attachment, 5: soil disker, 6: frame

Figure 3. Schematic diagram of APD-7.2

2.2.4 Soil and climatic characteristics of the Republic of Buryatia

Buryatia is in the center of the Eurasian mainland. The average annual air temperature is (−)0.5°C to (−)2.8°C. January is the coldest month, with average temperatures of (−)25°C to (-)35°C, at an absolute minimum; they can reach (−)40°C to (−)58°C. This leads to deep-freezing of the soil to a depth of 3–3.5 m. In July, the average monthly temperature reaches 15–25°C (Batudaev et al., 2010).

Annual precipitation is 250–340 mm. Chestnut soils comprise the greatest proportion of older plowed lands, which occur along steppe and intermontane depressions, and the southern slopes of ridges and foothills. These soils make up 60%–66% of the Republic's land area and about 42% of cultivated arable land (Bokhiev and Urbazaev, 1979; Batudaev et al., 2010).

Bokhiev and Urbazaev (1979) and Batudaev et al. (2010) note that the chestnut soils of Buryatia are significantly different from their analogs in the European part of Russia, especially with respect to the humus content. The former develop on light soil-forming rocks (sands, loam) in dry steppe conditions. They are referred to as loam, sandy loam, and sandy soils by virtue of their mechanical composition. The content of natural clay throughout the soil profile is no more than 30%; the fine sand fraction is 38–53%; the coarse dust is 10%–21% and the silt is 3%–12%. In contrast to similar soils in the European part of Russia, chestnut soils in Buryatia have a light granulometric composition. This feature determines their fundamental physical water properties: high overall porosity, high water permeability, low water retention capacity, and a small range of active moisture. To increase their yield, measures to save and accumulate moisture are first needed. Lack of moisture in the spring and early summer periods means that plants significantly reduce their productivity. Soil fertility has been measured as 13–15 points, which is almost two times lower than in western Siberia, and the agroclimatic potential is 0.46–0.48 (the average for Russia is 1) (Batudaev et al., 2010).

2.3 Results and Discussion

2.3.1 Costs and yields by different seeding technologies

Significant difference in favor of the seeding complex Kuzbass-8.5 in wheat cultivation on 1000 ha was found (Figure 4). This was explained by the machinery performing all operations inherent in conventional tillage in one pass.

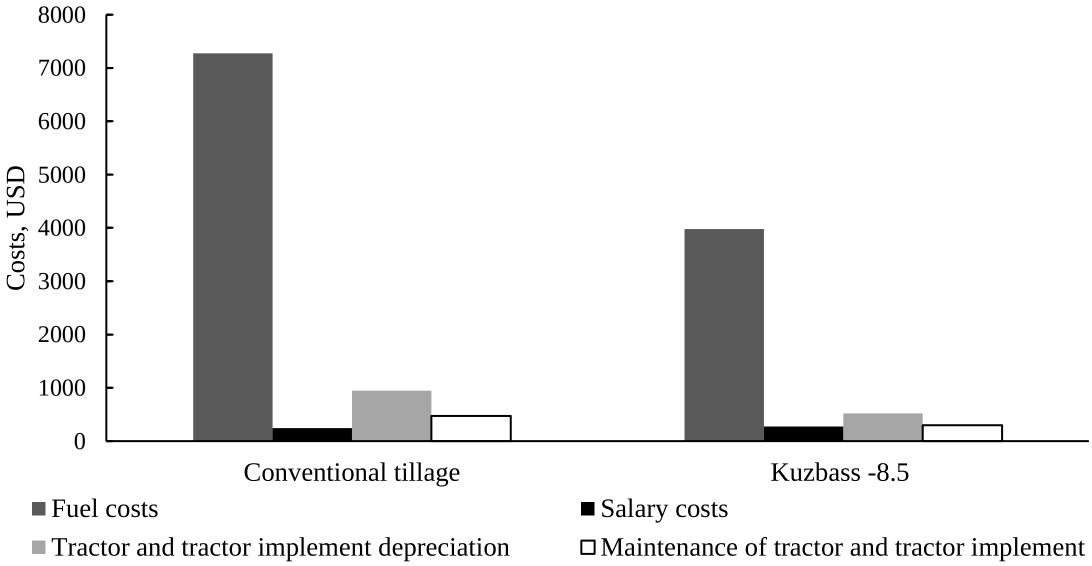
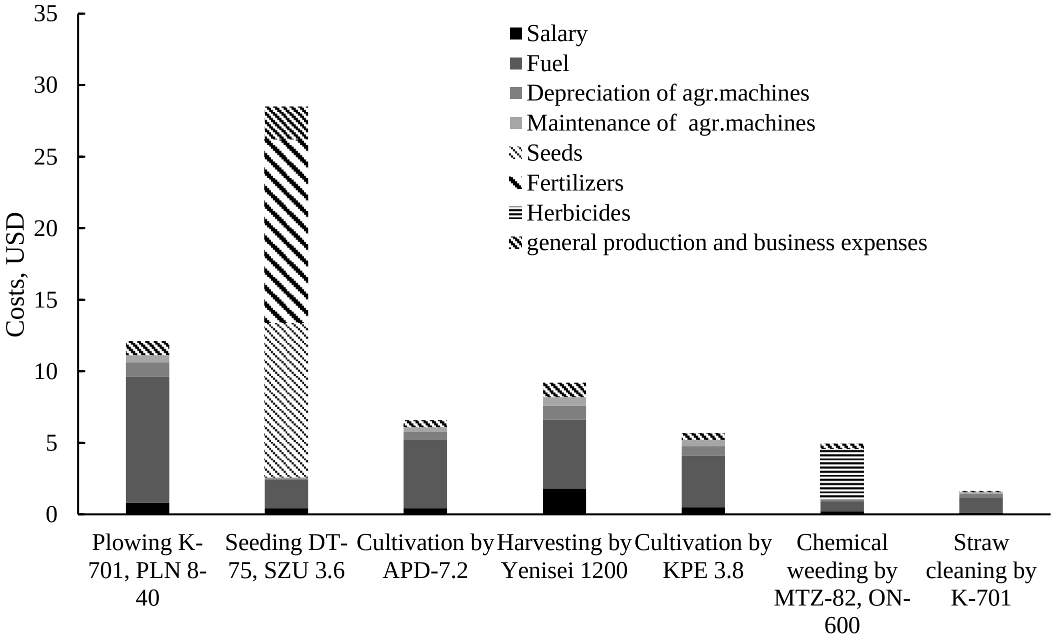
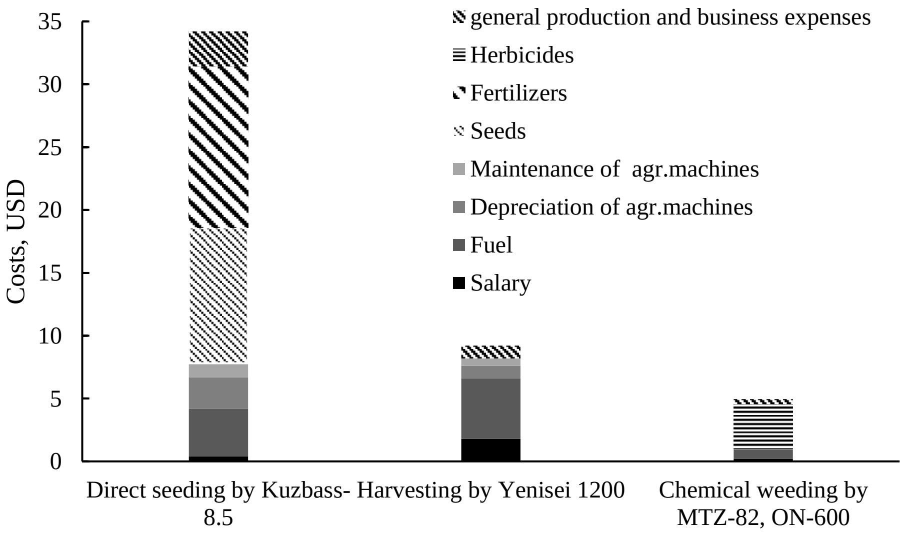


Figure 4. Conventional and minimum tillage for wheat seeding on 1000 ha

Calculations of the costs per hectare of arable land for various agro-technical works were made when comparing conventional and minimum tillage (Figure 5).



(a) Conventional Tillage



(b) Minimum Tillage

Figure 5. Cost comparisons for conventional and minimum tillage*

* Costs per ha of arable land for different agro-technical works

Figure 5 shows that the total cost for 1 ha was 65 USD for the following conventional sequence of technological operations during the vegetative period: spring plowing (K-701 + PLN 8-40), cultivation (K-701 + KPE-3.8), seeding (DT-75 + SZU-3.6), chemical weeding (MTZ-82 + ON-600), combining (Yenisei-1200), and straw harvesting (K-701). By including Kuzbass-8.5 (i.e., direct seeding) the cost was reduced by 24% to 52.5 USD for 1 ha.

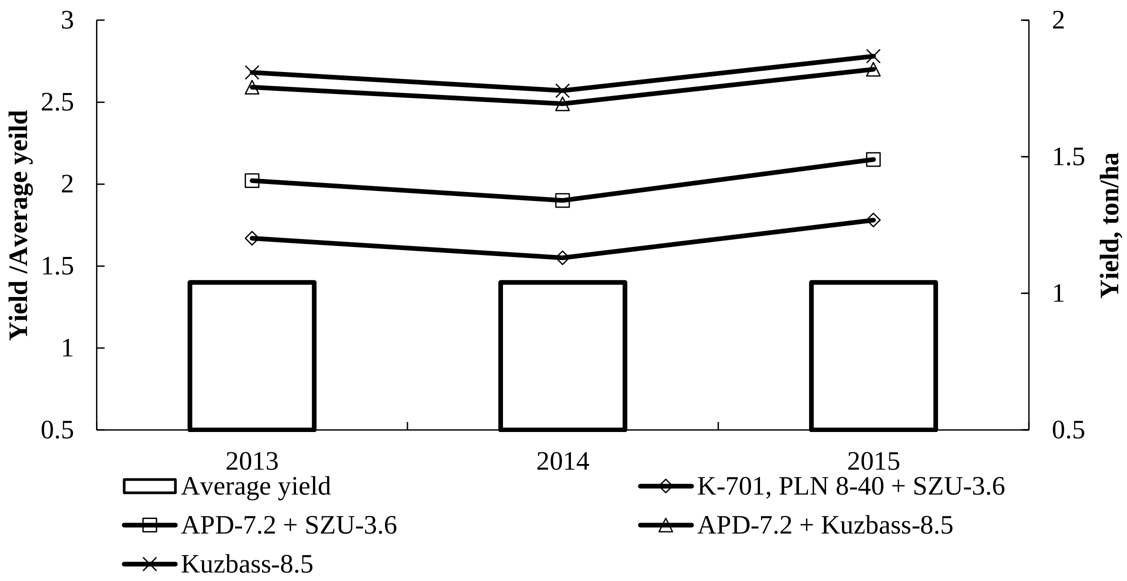


Figure 6. Yield of oats by different seeding technologies*

* A: Conventional. Moldboard plowing: K-701 and PLN 8-40. Separate seeding with SZU-3.6.

B: Resource saving. Cultivation with APD-7.2; separate seeding with SZU-3.6.

C: Resource saving. Cultivation with APD-7.2; seeding with Kuzbass-8.5.

D: Resource saving. Simultaneous cultivation and seeding with Kuzbass-8.5.

E: Average yield of oats throughout the Republic of Buryatia.

Figure 6 shows the ratio of yields obtained in a differentiated way to average yield of oats for Buryatia. It shows that within 3 years the highest yield was obtained with the direct seeding technology by Kuzbass-8.5. Almost the same yield of oats was obtained with APD-7.2 + Kuzbass-8.5 (minimum tillage). Therefore, the experiment has shown a high efficiency of using APD-7.2 and Kuzbass-8.5. Even in the hot, dry summer of 2014, there was no significant change in the yield of grain grown with minimum tillage and no-tillage. Hence, it can be concluded that the use of minimum tillage and no-tillage in grain cultivation is expedient and profitable. The soil tillage system influences the yields obtained in a differentiated way.

2.3.2 Carbon sequestration and humus content

Most land use changes significantly affect the amount of carbon sequestered in vegetation and soil, thereby shifting ecosystem carbon balance (Houghton, 2010). Mehra et al. (2018) suggest that future research should focus on monitoring the factors responsible for soil ecology and the “carbon-in” versus “carbon-out” equation when considering the contribution of minimum tillage and no-tillage technology in mitigating climate change. The profitability of conservation agriculture systems across a great diversity of cropping environments will ensure that local farmers will increasingly be convinced to adopt minimum tillage and no-tillage, and create a significant impact on maximizing global carbon sequestration. Increased farming operations efficiency will contribute to an overall mitigation of greenhouse gas emissions (Mehra et al., 2018).

Disintegration of the Soviet Union and the collapse of the collective farming system that followed led to abandonment of former croplands in Russia, including in the Republic of Buryatia. The area of agricultural land in Russia decreased from 639.1 million ha (as of

1 January 1990) to 400 million ha (as of 1 January 2010). Reductions were also noted in the Republic. From 1990 to 2010, agricultural land in Buryatia declined by 18.7 thousand ha (or 0.6%), and arable land by 122.6 thousand ha (or 12.8%). In 1990 arable land covered 954.6 thousand ha, hayfields 355.7 thousand ha, and pastures 1788.2 thousand ha; in 2010, these figures were 832.0 thousand ha; 389.8 thousand ha; and1858.0 thousand ha, respectively (Administration of the federal service of state registration, cadastre and cartography for the Republic of Buryatia, 2011).

These were the most widespread and abrupt land use changes in the northern hemisphere in the 20th century (Lyuri et al., 2010). The sudden withdrawal of croplands in the 1990s resulted in several environmental benefits, including substantial carbon sequestration in post-agrogenic ecosystems. Kurganova et al. (2015) estimated the total extra carbon sink in abandoned croplands in Russia to be 45.5 Mha, at a rate of 155 ± 27 Mt C/year. This additional carbon sink could cancel out about 18% of the global CO_2 released by deforestation and other land use changes, or compensate annually for about 36% of the current fossil fuel emissions from Russia. The extra carbon sink provided by post-agrogenic ecosystems in Russia contributes possibly about one-third of the total current carbon balance of the former Soviet Union (Kurganova et al., 2015). Hence, the disintegration of the former Soviet Union significantly affected the national and global carbon budget over a few decades after land use changes. Kurganova et al. (2015) also stated that the soil carbon buildup due to natural vegetation establishment occurs much more slowly than soil organic carbon losses after converting of grassland or forest to arable land. This should be borne in mind if, in future, there is a new expansion of unused land. Kurganova et al. (2015) conclude that the disintegration of the Soviet Union and the subsequent collapse of the collective farming system in the early 1990s had prolonged and positive ecological implications, including powerful effects on the carbon cycle and budget.

Long-term use (25 years) of minimum tillage to a depth of 8–10 cm for grains promotes the formation of a composite soil structure with a marked improvement in the agrophysical, agrochemical, and biological indicators of its upper layer fertility (Panov et al., 2008). Multifactorial field experiments carried out by scientists of the Moscow Agricultural Academy found that the humus content in the upper soil layer increased from 1.71% to 2.6%, soil density decreased from 1.4 to 1.2 g/cm^3, and the content of waterproof aggregates increased from 27% to 40% (Panov et al., 2008).

2.4 Conclusion and Implications

Minimum tillage and no-tillage systems present expedient, profitable alternatives to the conventional moldboard system of soil tillage because of increases in crop yield, reductions in cost, and to their conservation effects on the soil as compared with the conventional system. To date, resource-saving studies of Buryatia have concentrated mainly on cost factors. However, focus should be on the effects of systems and resource saving in terms of environmental resources, as only then can agricultural systems be sustainable and durable in agronomic, economic, and ecological terms.

The carbon enrichment of unplowed soils indicates that the conservation of soil organic matter contributes to carbon sequestration and lower impacts on global warming. We suggest, therefore, that future research into tillage methods in the Republic of Buryatia should focus on monitoring the factors responsible for soil ecology and the “carbon-in” versus “carbon-out” equation when considering the contribution of minimum and no-tillage technology to mitigating climate change.

The advantages of minimum and no-tillage soil systems in Buryatia can be used to improve methods in low-producing soils with reduced structural stability, as well as measures for water and soil conservation throughout the ecosystem.

Chapter 3

Optimum design of a chisel plow for grain production in the Republic of Buryatia, Russia

3.1 Introduction

The main types of soils on arable land of Buryatia are chestnut soil (43.2%), gray forest soil (22.5%), and black earth (12.3%) (Batudaev et al., 2010). During the Soviet period the traditional moldboard cultivation technology, which involves multiple passes of tractors and machines in the field has been used in the Republic of Buryatia. Theoretical and technological basis of farming were the recommendations developed in the central regions of the USSR. As a result, serious problems of soil compaction and fertility preservation of arable land have arisen and become acuter every year.

There are two significant issues in the basic process of soil tillage: energy and environmental problems. While energy cost increase rapidly due to the operation of a large range of machines, the environmental problem arises from the mechanical impact on the soil, resulting in wind and water erosion. Consequently, the importance of developing technological solutions with regard to energy saving and soil protection criteria become crucial (Beluchenko, 1996).

The most promising soil protective, resource-saving technology currently in the Republic of Buryatia is minimum tillage. The minimum tillage method presupposes the use of subsoil and deep soil tillage devices, such as the chisel plow. In farming, chisel plows are designed for subsoil tillage of compacted soil layers that prevent natural air and water exchange. Shanks with a chisel knife form the slits, through which there is an exchange of oxygen and moisture to the underlying layer of soil. This process improves the condition of the surface layer. Determining the optimal design of a chisel plow allows for efficient use of energy and material resources (Davletshin and Tihonov, 2012; Tsvetkov et al., 2012). However, there is insufficient knowledge of optimal parameters for chisel plows.

The purpose of this study was to develop an advanced, resource-saving chisel plow for grain production in the Siberian region, which includes the Republic of Buryatia. The chisel plow design was optimized by decreasing its mass and increasing its service life, using the finite element method (FEM). The proposed design reduced resistance of soil to the working parts and increased operational reliability of the device.

FEM has become the leading way to reach numerical solutions in evaluating the most significant physical and mechanical features of details, units, and machines, which often arise in the process of machine building. FEM allows elimination of the disadvantages of the original plow model and optimizes its shape. Among the weaknesses of the original model were high energy consumption during soil tillage, low operational reliability, and poor quality of soil crumbling (Alyamovskiy, 2007; Feng and Moses, 1986).

3.2 Materials and Methods

3.2.1 Materials

The original chisel plow model had a shank of six holes for attachment to the frame and fixing the ‘shank–chisel knife’ with two bolts in the longitudinal vertical plane. The material properties are given in Table 2 (Zhang et al., 2012).

Table 2. Material properties

Property	16 Mn	65 Mn
Density (kg/m^3)	7850	7820
Young’s modulus (Pa)	2.12×10^{11}	2.11×10^{11}
Poisson ratio	0.31	0.29
Yield strength (Pa)	3.45×10^{8}	7.85×10^{8}
Tangent modulus (Pa)	7.94×10^{10}	7.94×10^{10}
Tensile yield stress (MPa)	470	735
Ultimate strength (MPa)	660	981

3.2.2 Methods

3.2.2.1 FEM

The essence of FEM is to substitute basic isometric construction with complicated geometric forms by use of a discrete mathematical model that keeps the physical essence and features of the basic detail. The most important part of this model is construction of elementary volume complexes of pre-assigned form united in a finite element composed mesh (Arora, 1989; Inshakov and Natalenko, 2005).

In the present study, the use of specialized software allowed the applying of FEM to static analysis (Araya and Gao, 1995; Basov, 2014; Kaplun et al., 2015). The method has three main parts: the determination of properties of the mechanical structural materials, using static analysis; a shape optimization analysis that requires determining the subsoil chisel structure; and mathematical data processing of the chisel model with the response to surface method and the global optimization method. The model with preset parameters was run and the optimization results determined. The modeling methods include different parameters and main steps for desired shape construction (Abo Al-kheer et al., 2011; Bate and Wilson, 2012; Trushin, 2008). FEM is a numerical solution for structural analysis that demonstrates its applications with ANSYS (Yong and Hanna, 1977).

The meshing is the conversion of a whole model into a number of small elements. Different kinds of meshing are used in the pre-processing and, in the present study, tetrahedral mesh was used for high accuracy. The number of elements represents the solution accuracy of the model (Kharmanda et al., 2009).

3.2.2.2 Shape optimization

Nine parameters for shank shape optimization were used: shank length, handle thickness, bolt hole depth, bolt hole diameter, bolt hole position, abscissa A in central ditch, ordinate A in central ditch, abscissa B in central ditch, ordinate B in central ditch, central ditch depth, and central ditch width (Figure 13 a).

3.2.2.3 Mathematical methods

Mathematical data processing during the development of the chisel shank model was used with the response to the surface method. The global optimization method was maintained for the determination of the parameter values of the best model. Finally, the model characteristics before and after the improvement were compared.

General elements of the chisel plow optimization analysis using appropriate software are shown in Figure 7.

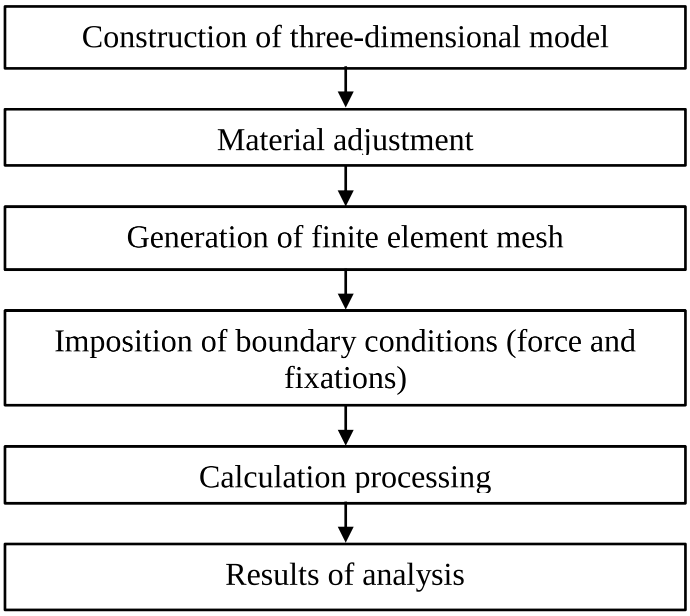


Figure 7. Phases of finite element analysis of construction

3.3 Results and Discussions

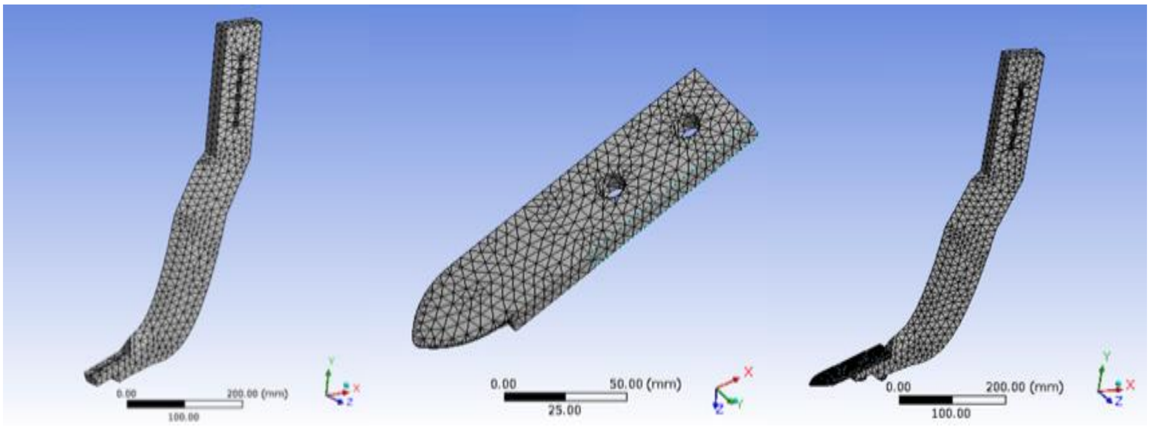
3.3.1 Results of the static analysis of the original chisel plow model

The mesh view of the original shank, knife, and chisel plow after assembly is given in Figure 8. The static analysis was used to assess the structural deformation and stress state quantitatively. A description of the original chisel plow model is given in Table 3.

Table 3. The original chisel plow model description

	Material, steel	Mass (kg)	Mesh (mm)	Number of elements	Number of nodes	Force (N)
Shank	16 Mn	12.68	15	5224	8927	X +3500 Y −2500
Knife	65 Mn	0.43	5	4582	7888	X +3500 Z +2500
Assembled	16 Mn; 65 Mn	13.22	15; 5	11142	19846	X +3500 Y −2500

The shank material of the original model was 16 Mn steel (Young's modulus 2.12 × 1011 Pa and Poisson's ratio 0.31). Shank model mass was 12.68 kg. The total number of the finite element model was 5224 and the total number of nodes 8927 (Figure 8a). For control distribution under the mesh, the shank and knife were divided into finite elements 15 and 5 mm, respectively (Figure 8).



(a) shank (b) knife (c) assembled

Figure 8. Meshed model

The chisel knife of the original model had a simple structure (Figure 8b), with 65 Mn steel as the material, because it possesses good mechanical properties. It weighed 0.43 kg. The total number of the model finite elements was 4582 and the total number of nodes 7888.

Force and fixation conditions were used as boundary conditions. The surface of the chisel knife was connected with a shank and fixed by six bolts. To determine elastic deformation to the toe of the chisel knife, forces of +3500 N in the X direction and −2500 N in the Z direction were applied (Figure 9). According to the previous studies, the static force matches the dynamic force required for chiseling at a depth: 300; 350;400 mm; and at speed: 4; 4.5; 5 km/h. Based on this knowledge we use 4301.2N of +3500 N in X axis and -2500 N in Z axis (Zhang et al., 2012).

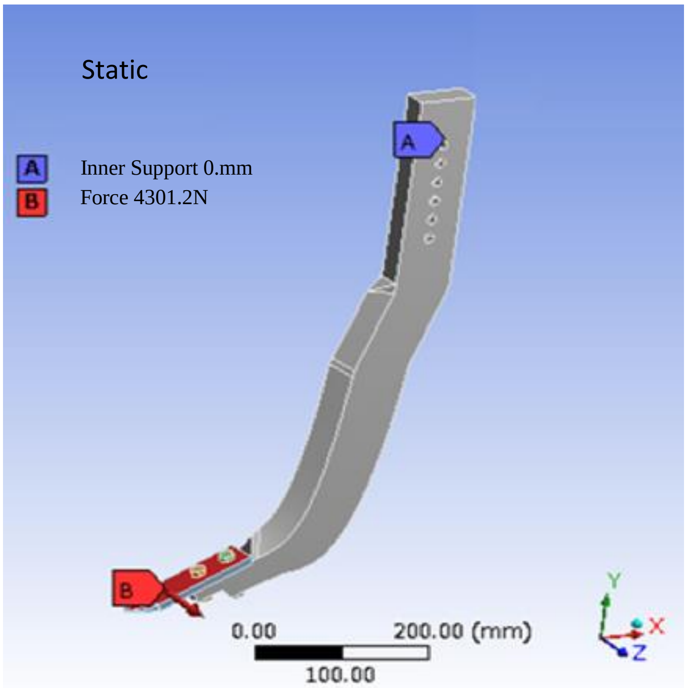


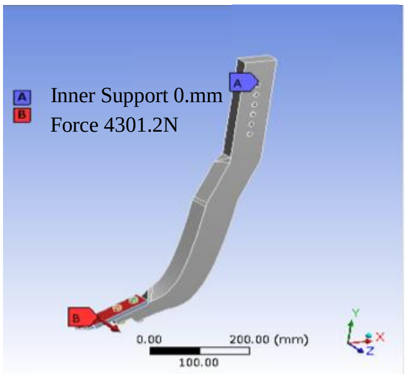
Figure 9. Boundary conditions

The software reports the results of the analysis as a three-dimensional model, giving different zones various colors that correspond with the range of the appropriate physical feature. Four types of analysis were applied to the original chisel plow model.

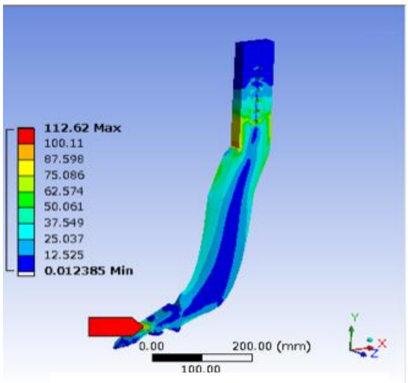
For the original chisel plow model, after assembly and under the action of the force, the maximum equivalent stress was 112.62 MPa, the maximum equivalent elastic strain was 5.34×10^{-4}, and total deformation was 1.48 mm (Figure 10). The results of the static analysis of the original chisel plow model are given in Table 4.

Table 4. Results of the static analysis of original chisel plow model

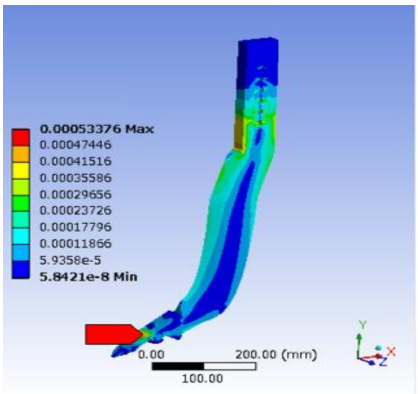
	Mass (kg)	Equivalent stress (MPa)	Equivalent elastic strain (mm/mm)	Total deformation (mm)
Shank	12.68	105.24	4.96×10^{-4}	0.99
Knife	0.43	170.15	8.0642×10^{-4}	0.28
Assembled	13.22	112.62	5.3376×10^{-4}	1.48



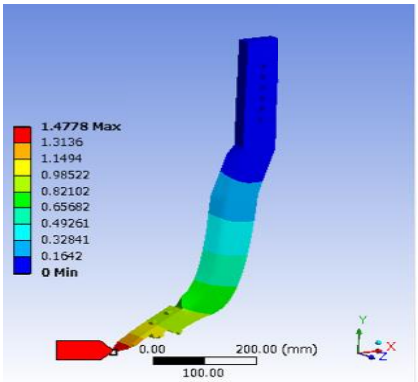
(a) Boundary conditions



(b) Equivalent stress



(c) Equivalent elastic strain



(d) Total deformation (mm)

Figure 10. Results of static analysis for the original model

3.3.2 Shape optimization

Shape optimization results for the shank of the chisel plow are given in Figure 11. In real conditions, the program calculations are difficult to implement. By considering the initial parameters and the results of the static analysis, it was decided to reduce the mass of the part by 8% instead of the 20% offered by the program.

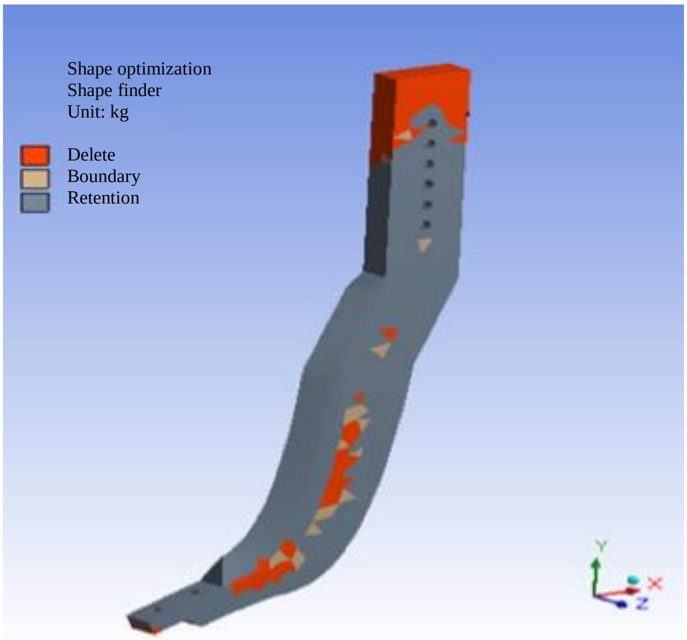


Figure 11. Results of shape optimization for the shank

The chisel plow works under three balanced forces (Figure 12). The static analysis demonstrated that the original model had the equivalent stress of 170.15 MPa and ultimate tensile strength of 981 MPa. Thus, deformation change to the chisel plow was minor, and the static analysis results confirmed this. Therefore, it was decided to change the shank and knife fixation.

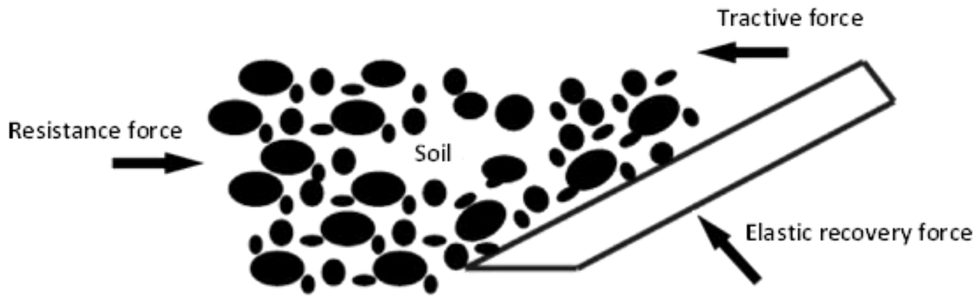
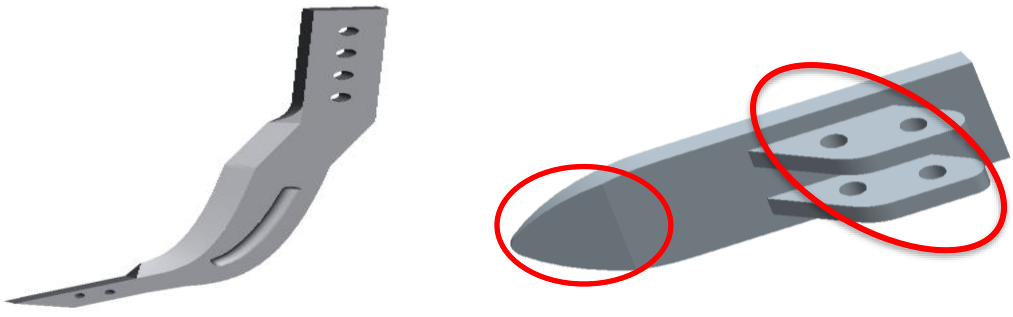


Figure 12. Mechanical analysis of knife of the chisel plow

The chisel shank and chisel knife after optimization of the three-dimensional model effect are shown in Figure 13. The mesh view of the optimized shank, a knife, and assembled chisel plow is given in Figure 14. The description of the optimized chisel plow model is given in Table 5.

Table 5. The optimized chisel plow model description

	Material, steel	Mesh (mm)	Number of elements	Number of nodes	Force (N)
Shank	16 Mn	15	5420	9432	X +3500 Y −2500
Knife	65 Mn	5	12688	20853	X +3500 Z +2500
Assembled	16 Mn; 65 Mn	15; 5	11142	19846	X +3500 Y −2500



(a) (b)

Figure 13. Chisel shank (a) and knife (b) after optimization of the 3D model

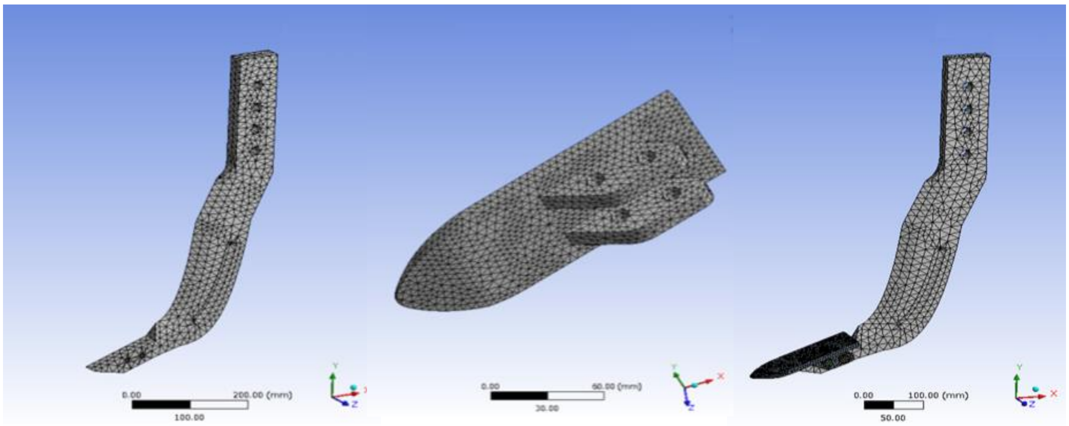


Figure 14. Meshed optimized model

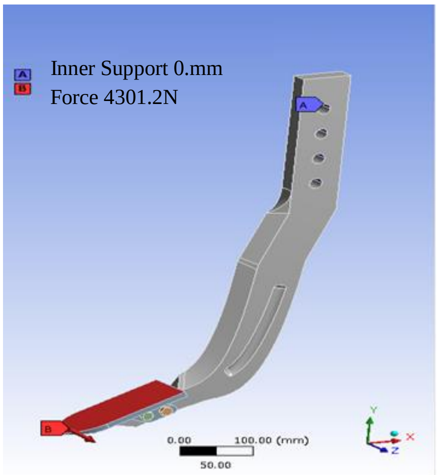
3.3.3 Results of static analysis of the optimized chisel plow model

The optimized model of the chisel plow, after assembly and under the action of the force, had maximum stress of 107.42 MPa, the maximum elastic strain of 5.07×10-4 mm/mm, and total deformation of 1.45 mm (Figure 15). The results of the static analysis of the original model are given in Table 6.

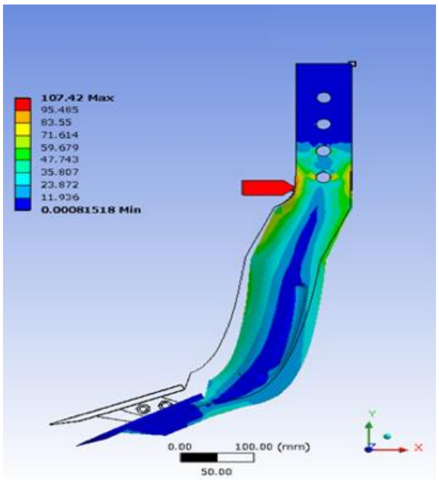
Table 6. Results of the static analysis of optimized model

	Mass (kg)	Equivalent stress (MPa)	Equivalent elastic strain (mm/mm)	Total deformation (mm)
Shank	10.75	88.56	4.18×10^{-4}	0.98
Knife	1.29	27.79	1.32×10^{-4}	0.027
Assembled	12.16	107.42	5.07×10^{-4}	1.45

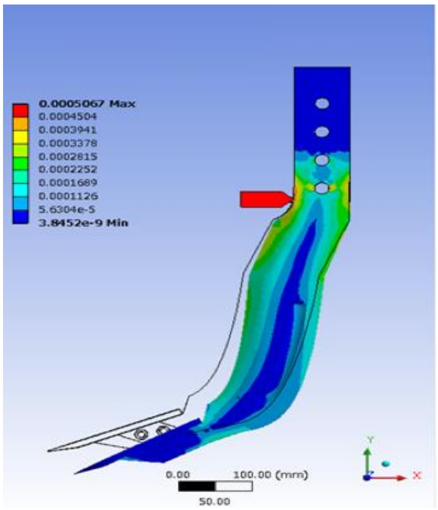
The results indicated that for the same action of force, the maximum equivalent stress of the optimized model decreased by 4.6%, the maximum equivalent elastic strain of the optimized model decreased by 2.1%, and total deformation of the optimized model decreased by 5%; additionally, a mass of optimized construction decreased by 8%. Total deformation for the knife is 0.027 mm. The knife deformation is one tenth of the original since the modification occurred in the chisel shank structure, specifically in the edge shape where the knife is attached, total deformation for knife decreased from 0.28 to 0.027.



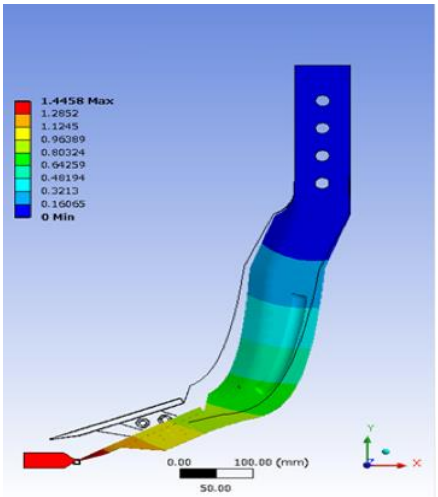
(a) Boundary conditions



(b) Equivalent stress (MPa)



(c) Equivalent elastic strain (mm/mm)



(d) Total deformation (mm)

Figure 15. Results of static analysis for the optimized model

3.3.4 Parametric results

The parametric results concerning equivalent stress, equivalent elastic strain, total deformation, and mass showed that the optimized model of chisel plow was more practicable than the original. Construction of the optimized model of the chisel plow was also more practicable for farm use. The proposed model reduced resistance of soil to the working parts and increased operational reliability of the device, as well as the quality of tillage.

3.4 Conclusion

An optimum design of chisel plow for grain production in the Republic of Buryatia was developed to solve the problem concerning energy saving and soil protection criteria. The proposed model reduced resistance of soil to the working parts and increased operational reliability of the device, as well as the quality of tillage.

Data of the equivalent stress, equivalent elastic strain, total deformation, and mass were obtained using the FEM to determine the optimum design of the chisel plow; these values for the optimized construction have decreased by 4.6, 2.1, 5, and 8% compared with the original design, respectively. Optimization of the chisel plow design was achieved by decreasing its mass and increasing its service life.

The results of the analysis depend on the physical and mechanical properties of the soil. Further experiments in real farm conditions are necessary to verify the analysis and determine the degree of discrepancy.

Chapter 4

Development of Deep Placement Fertilizer Applicator (DPFA) for Grain Production in Russia

4.1 Introduction

It was concluded in the previous chapters, that the application of the minimum tillage and no-tillage systems present advantageous and profitable alternatives to the conventional system of soil tillage.

Nowadays there is a gap between the equipment available in the Russian market and agricultural stakeholders need for the equipment embracing modern technologies for grain cultivation. Therefore, the purpose of this study is to develop a resource-saving DPFA prototype for grain production in Russia. Deep introduction of fertilizers is one of environmentally friendly farming method. It allows to improve efficiency in fertilizer use (Mohanty et al., 1999) and increases yield (Takahashi et al., 1991) and grain quality by maintaining the effect of fertilizers over a longer period. Deep introduction of fertilizers into the zone most saturated with roots is particularly important for grain crops development. It stimulates the growth and development of roots. Most researchers who studied the depth of the grain roots concluded that the bulk of roots is in the soil horizon of 8-20 cm (Fana et al., 2016). The depth of the root system also depends on the type and degree of moistening of the soil. Deep placement of fertilizers provides more air available to the roots of plants, which contributes to their better development. The effectiveness of deep placement of fertilizers is also attributed to the fact that sufficient amount of moisture in the soil at a depth ensures the supply of plants with nutrients for the entire period of vegetation. Thus, better conditions for the development of its root system are obtained.

4.2 Materials and Methods

A counterpart of this research, as a scientific and practice sector collaboration, is Mr. Anatolii Stacenko. He is one of the most prominent farmers of the Primorskii region, Russian Federation. The total arable land area of his farm is 5000 hectares. Wheat, rye, barley, oats, soybean are cultivated on this farm. We have collaborated since 2015. Inspired by Mr. Stacenko' extensive knowledge and long experience in agriculture, we felt it necessary to fill the gap between the equipment available in the Russian market and agricultural stakeholders' need for the equipment embracing modern technologies for grain cultivation. Our cooperation resulted in the creation of a scheme of a new prototype seeder for grain production in Russia (Figure 16).

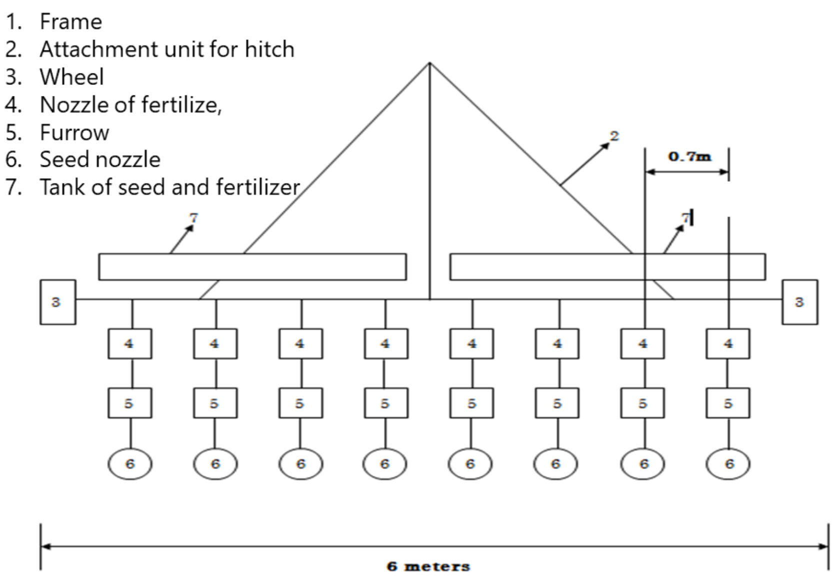


Figure 16. Schematic diagram of grain seeder

The optimum design of chisel plow for grain production in the Republic of Buryatia (Chapter 3) was utilized for this implement since it had been proven to comply with energy saving and soil protection criteria. The scheme includes a frame, attachment unit for the hitch, wheels, nozzles for fertilizer application, chisels, nozzles for seed application, tanks for seeds and fertilizers. The working width of the seeder is 6 meters, the width between the rows is 0.7 meters.

Solidworks simulation software 3DCAD (Solidworks 2015, Dassault Systems, Co., Ltd.) was used for designing the Deep Placement Fertilizer Applicator. Also, the comparison between theoretical calculations of the safety factor and its simulation in 3D software SolidWorks was conducted.

4.3 Results and Discussions

4.3.1 Overview of seeding machines in Russia

The creation and use of combined machines that perform several technological operations in a single pass have become one of the main directions for introducing resource-saving technologies in the cultivation of crops. Since the domestic industry currently does not produce high-performance wide-spread seeders, farmers exploit multi-section (three- and four-) seeding units from traditional seeders with joints SP-11A and SP-16 mounted on the tractors of traction classes 3 and 5 (27-36 kN and 45-54 kN respectively). Their productivity is unsatisfactory. When moving equipment from one field to another on public roads, it is necessary to disconnect the seeders from the joints and build it in a "train," which requires the efforts of two or three people.

The need to develop equipment competitive in the world market and oriented at the maximum productivity at commensurate costs has grown in the Russian market (Radnaev, 2010).

Mainstream domestic seeding machines include:

Universal grain seeder (SZU-3.6) is equipped with replaceable adapters for subsoil-spreading with the simultaneous packing of soil by the roller. Furrow opener makes it possible to distribute the seeds in the optimum nutritious soil zone and to do so without pre-plant cultivation. This seeder performs soil preparation and sowing in three operations instead of nine, necessary for the traditional technology.

The seeding complex Kuzbass-8.5 performs cultivation, harrowing, seeding, application of fertilizers, packing, leveling the soil, seed dressing in a single pass. With the use of this complex, the time gap between soil preparation and seeding that is typical for traditional domestic technology is being eliminated. Favorable conditions are created for germination and the formation of a normally developed plant in the future.

Universal pneumatic seeder S-6PM2 is designed for sowing cereals, medium-legumes (peas, lupins, and others), cruciferous (rape, radish oil), clover, timothy grass, alfalfa and other grass seeds with the simultaneous application of granulated mineral fertilizers. Seeder S-6PM2 is aggregated with tractors of traction class 1,4 and 2,0; its working width is 6 m.

4.3.2 The DPFA prototype

The new Deep Placement Fertilizer Applicator (DPFA) prototype was developed. This model has two distinctive features. First, it can perform deep placement fertilization, which is one of environmentally friendly farming methods. Second, this implement can save on labor costs because it simultaneously performs tillage, fertilization, and seeding. Furthermore, the top dressing is not required because the effect of fertilizers is kept over a longer period by the deep placement fertilization. The proposed chisel plow model reduced resistance of soil to the working parts and increased the operational reliability of the device.

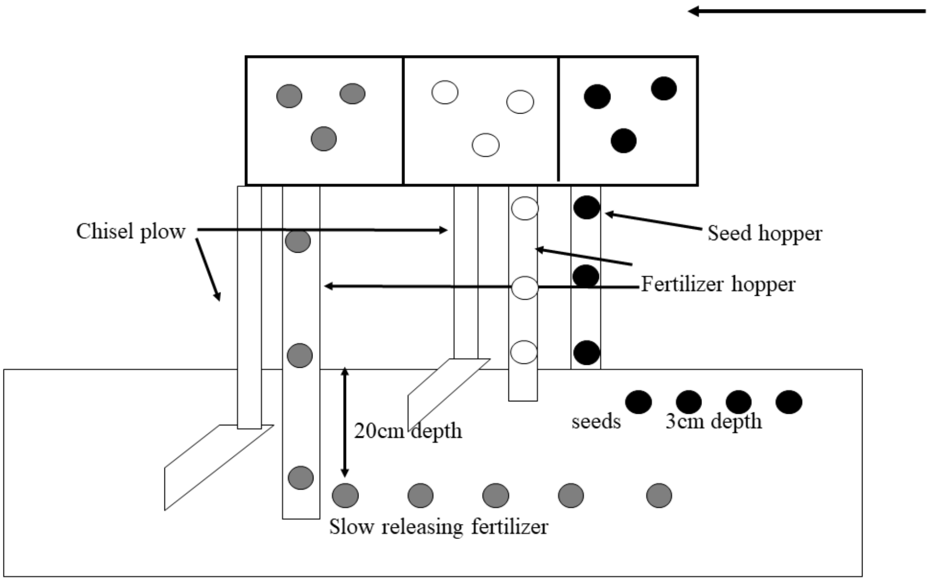


Figure 17. Scheme of Deep Placement Fertilizer Applicator

Figure 17 shows the mechanism of DPFA. Fertilizers are distributed into deep soil layers by long pipes running behind the chisel plow. The prototype working width is 6 meters. Tillage method is a minimum tillage by the chisel plow optimized in the Chapter 3 (Figures 19, 20, 21). The prototype has three sections; a tank for seeds and fertilizers, the chisel plows, pipes for fertilizer delivery to the depth of 20 cm, fertilizer hoppers and seed hoppers for the application to the depth of 3 cm. The 3-Dimensional model of DPFA is presented in Figure 18.

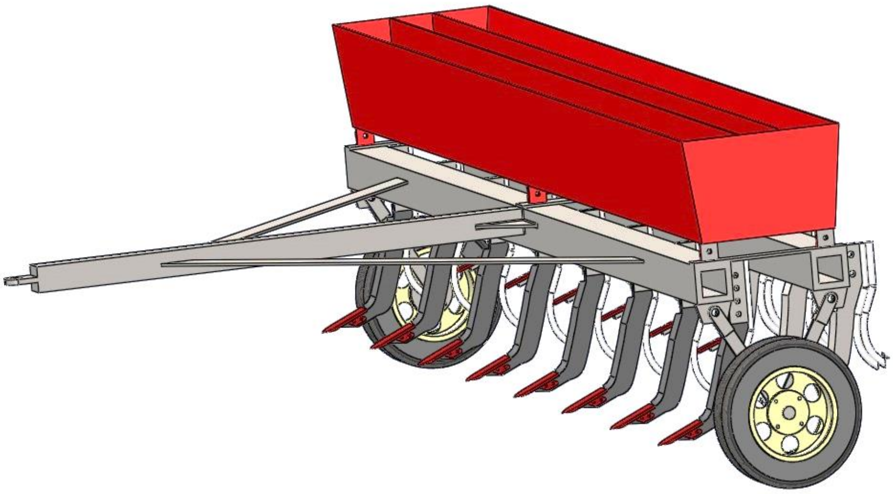


Figure 18. 3D model of DPFA

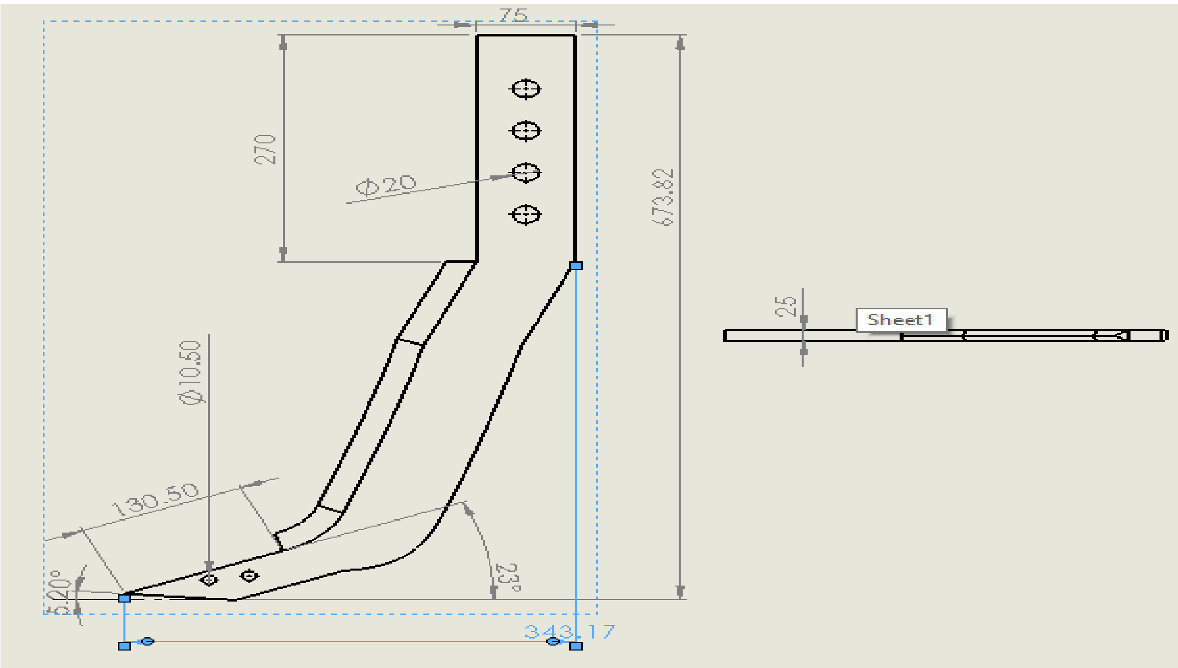


Figure 19. Shank of chisel

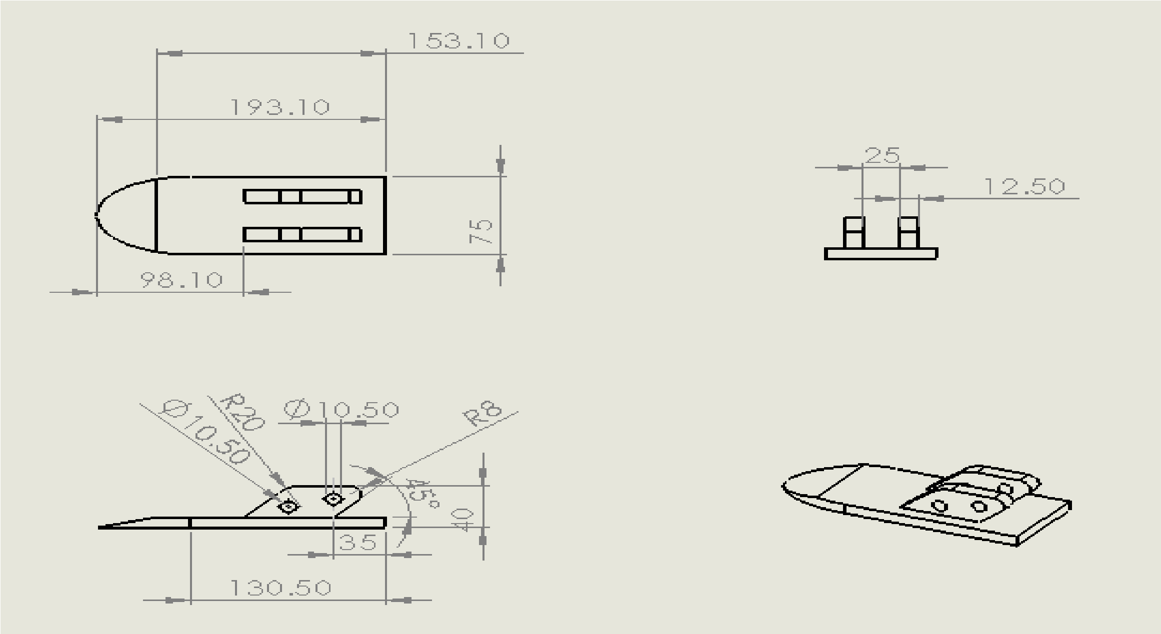


Figure 20. Knife of chisel

Figure 21. 3D model of chisel plow

4.3.3 The fabrication of the DPFA

From November 2017 a Pilot Project "Search for high protein soybean and development of high-speed DPFA for large-scale farming in the Russian Federation Far East"(Project) was launched between Niigata University and Primorskaya State Academy of Agriculture. Development of seeder with DPFA applied in the large-scale Russian farming is the main purpose of the Project. The idea, the 2D and 3D engineering drafts of the DPFA were submitted to the Primorskaya State Academy of Agriculture for further fabrication on November 1, 2017. The fabrication of the proposed chisel plow was made during the first stage of the Project. Test-work and evaluation of the fabricated prototype on the field are planned to be held from May to September 2018.

4.3.4 Safety factor comparison between theoretical calculations and SolidWorks simulation

According to the theoretical calculations for the Project, total resistance of one chisel is 1806 N and the strength condition is 4291 N, which is more than 2-fold margin. Consequently, the theoretical safety factor can be determined as follows:

$$SF = R_{Fmax} / R_F \qquad (1)$$

where SF is the safety factor.

As a result, theoretically determined safety factor is 2.37. According to the simulation in SolidWorks, the safety factor of chisel plow is 2.2 (Figure 22). Results of the theoretical calculations and the software simulation are approximately equal.

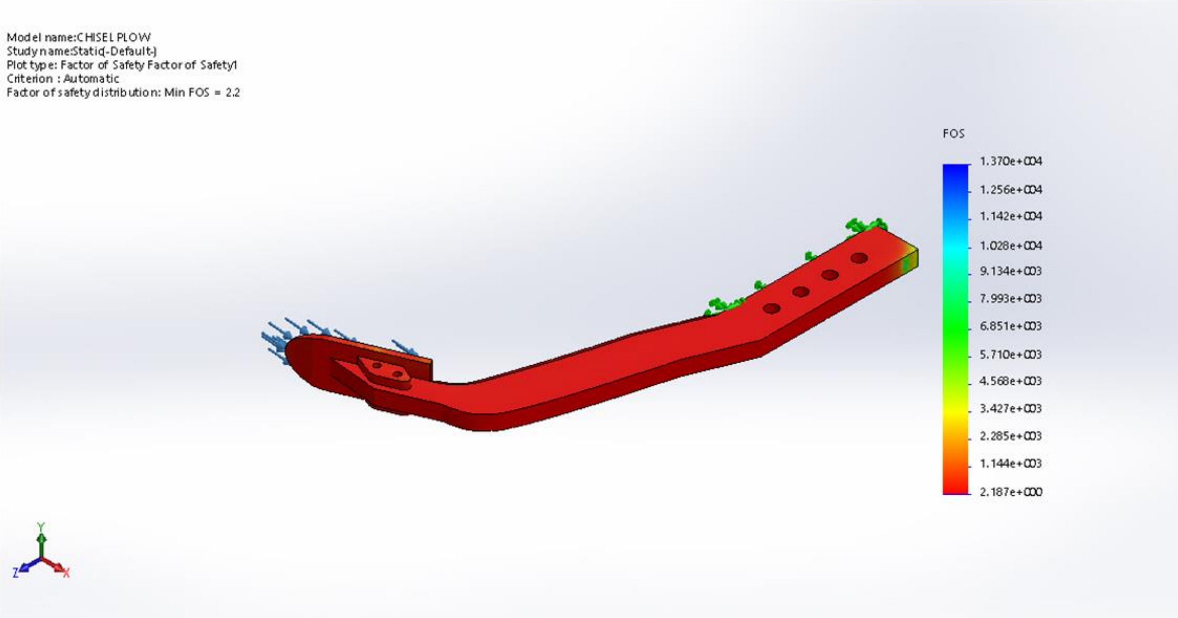


Figure 22. Safety factor of chisel plow

Safety factor interpretation:

A safety factor less than 1.0 at a location indicates that the material at that location has failed.

A safety factor of 1.0 at a location indicates that the material at that location has just started to fail.

A safety factor larger than 1.0 at a location indicates that the material at that location is safe.

Assuming that the stresses/strains remain in the linear range, the material at a location will start to fail if one applies new loads equal to the current loads multiplied by the resulting factor of safety. Requirement of a minimum safety factor is between 1.5 and 3.0 (SolidWorks Online Help, 2012). It can be concluded that new chisel is reliable.

4.4 Conclusion

The new Deep Placement Fertilizer Applicator prototype was developed. This model has mainly two features. At first, it can perform deep placement fertilization, which is one of environmentally friendly farming methods. Second, this implement can save on labor costs because it simultaneously performs tillage, fertilization and seeding. Furthermore, additional top-dressing application is not required because the effect of fertilizers is kept over a longer period by the deep placement fertilization.

The fabrication of the DPFA was applied in Pilot Project "Search for high protein soybean and development of high-speed DPFA for large-scale farming in the Russian Federation Far East". Subtitle for the Primorskaya State Academy of Agriculture (member of the Project): Development of seeder with deep fertilizer placement applied in the Russian farming. The idea, the 2D and 3D engineering drafts of the DPFA were submitted to the Primorskaya State Academy of Agriculture on November 1, 2017. The fabrication of the proposed chisel plow was made during the first stage of the Project. Evaluation on the field and test results will held from May to September 2018.

Chapter 5 Conclusion

The minimum tillage and no-tillage systems present expedient and profitable alternatives to the conventional system of soil tillage, due to crop yield increase, cost reduction and to their conservation effects on the soil as compared to the conventional system. Environmental effect and resource-saving in terms of environmental resources should be in the focus due to only then the agricultural system can be sustainable-durable in agronomic, economic and ecological terms.

The new DPFA prototype with optimized chisel plow for grain production was developed. The optimum design of chisel plow allows to solve the problem concerning energy saving and soil protection criteria. The proposed model reduced resistance of soil to the working parts and increased operational reliability of the device. Data of the equivalent stress, equivalent elastic strain, total deformation, and mass were obtained using the FEM to determine the optimum design of the chisel plow; these values for the optimized construction have decreased by 4.6, 2.1, 5, and 8% compared with the original design, respectively. Optimization of the chisel plow design was achieved by decreasing its mass and increasing its service life.

The new DPFA prototype has mainly two features. At first, it can perform deep placement fertilization which is one of environmentally friendly farming method. Second, this implement can save on labor costs because it simultaneously performs tillage, fertilization and seeding. Furthermore, top dressing application is not required because the effect of fertilizers is kept over a longer period by the deep placement fertilization. It can be used to improve methods in low producing soils with reduced structural stability, as well as measures of water and soil conservation on the whole ecosystem.

From November 2017 a Pilot Project "Search for high protein soybean and development of high-speed DPFA for large-scale farming in the Russian Federation Far East" (Project) was launched between Niigata University and Primorskaya State Academy of Agriculture. Development of seeder with DPFA applied in the large-scale Russian farming is the main purpose of the Project. The idea, the 2D and 3D engineering drafts of the DPFA were submitted to the Primorskaya State Academy of Agriculture for further fabrication on November 1, 2017. The fabrication of the proposed chisel plow was made during the first stage of the Project. Test-work and evaluation of the fabricated prototype on the field are planned to be held from May to September 2018. The results of the analysis depend on the physical and mechanical properties of the soil. Further experiments in real farm conditions are necessary to verify the analysis and determine the degree of discrepancy.

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Appendix 1

From the report on Project research work: Development of a seeder with Deep Placement fertilizer applicator applied in the Russian farming

Figure 1. General view of the seeder (front view – side view)

1.1 Determination of the seeder tractive resistance

The total tractive resistance of the seeder can be defined as follows:

$$R = R_1 + R_2, \tag{1}$$

where R_1 is tractive resistance of the knife, N; R_2 is working tractive resistance of chisel, N.

The seeder resistance can be determined as follows:

$$R_1 = K \cdot n, \tag{2}$$

where K is soil resistance during the work of a knife (at a seeding depth of 6 cm, k = 70 ÷ 125 N [1]); n is number of knives.

Having assumed the maximum possible resistance of the soil, we obtain $R_1 = 500\ N$.

The resistance of chisels is defined as follows:

$$R_2 = (F_1 + F_2) \cdot Z, \tag{3}$$

where F_1 is resistance of chisel knife, N; F_2 is resistance of chisel shank, N; Z is number of chisels.

Resistance of chisel knife and chisel shank were determined, respectively:

$$F_1 = A_k \cdot в_1; \tag{4}$$

$$F_2 = A_s \cdot в_2, \tag{5}$$

where A_k and A_s are areas of the chisel knife and chisel shank respectively, mm^2; $в_1$ and $в_2$ are soil resistivity of the subsurface and plow-layer respectively N/mm^2.

For heavy loamy soils [1] $в_1 = 0.12\ N/mm^2$; $в_2 = 0.08\ N/mm^2$.

Taking into account the geometric parameters of the chisel knife and chisel shank (Figure 1), we obtain $F_1 = 1557$ N, $F_2 = 249$ N.

The total resistance of one chisel will be:

$$R_F = F_1 + F_2 = 1806\ N. \tag{6}$$

The total resistance of all chisels of the seeder in accordance with the equation (3) will be equal to: $R_2 = 7224$ *N*.

The total tractive resistance of the upgraded planter, taking into account the equation (1), will be determined as follows: $R = 7728$ *N*.

1.2 Force analysis of chisel shank

Boundary conditions of chisel plow are presented in Figure 2.

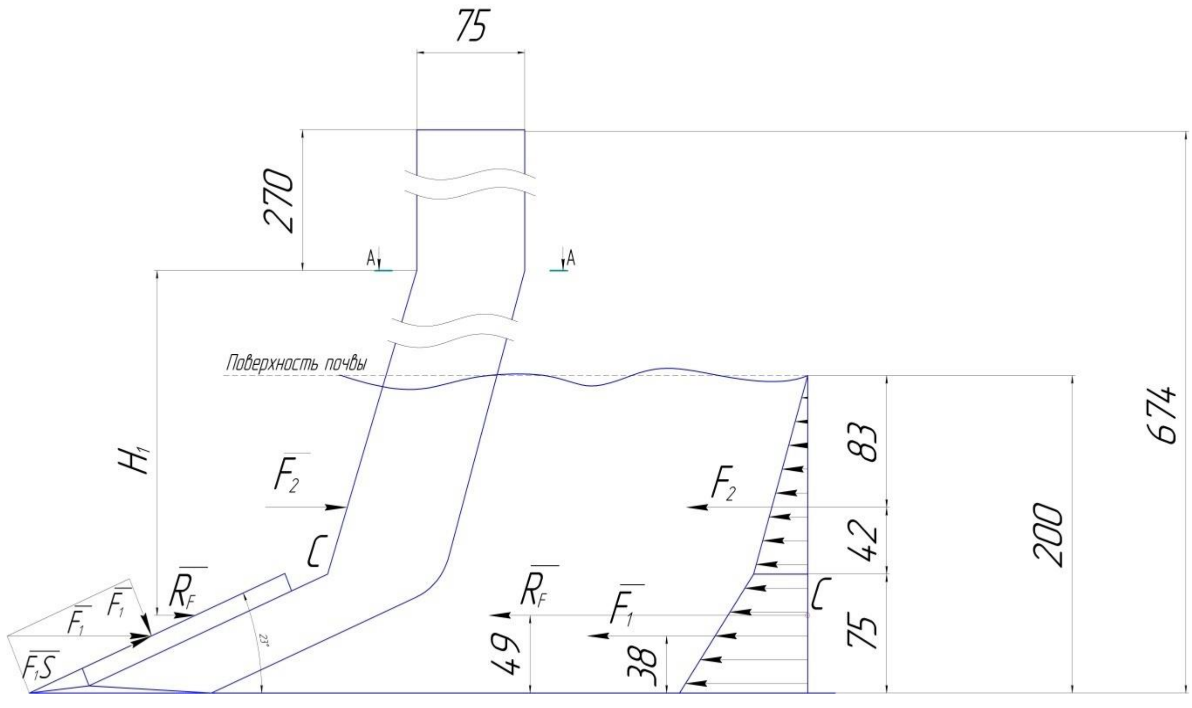

Figure 2. Boundary conditions of a chisel plow

According to forces F1 and F2 presented in Figure 2, the equalizing force of the chisel resistance will be applied in the coordinate (point C) along the OX axis, which can be found from the expression, as the coordinate of the center of parallel forces:

$$X_c = \frac{1}{R_F} \cdot F_1 \cdot X_{c1} \quad (7)$$

$$X_c = 48.8 \approx 49 \text{ mm}$$

Then, knowing the point of application and the direction of the force vector of the total tractive resistance of chisel R, we can determine the strength criteria in the dangerous section of shank and in the fasteners.

The most dangerous part of the chisel shank from the action of the bending moment will be the cross-section of the AA shank given the presence of a stress concentrator in the form of a passing angle.

The strength condition in the section under consideration is expressed as follows:

$$G_{max} = \frac{M}{W} \leq [G], \qquad (8)$$

where M is the bending moment, Nmm; W is the moment of shank resistance, mm^3.

The bending moment of total resistance of the chisel will be:

$$M = R \cdot H_1. \qquad (9)$$

The moment of resistance of a rectangular section [3] of a chisel shank:

$$W = \frac{b \cdot h^2}{6} \qquad (10)$$

Then the safety factor takes the form:

$$G_{max} = \frac{6M}{b \cdot h^2} \leq [G] \qquad (11)$$

or

$$G_{max} = \frac{6 \cdot R_F H_1}{b \cdot h^2} \leq [G]. \qquad (12)$$

With the allowable bending stress for structural steel, taking into account the safety margin, we take $[G] = 65\ N/mm^2$ [3].

Then from equation (12) we define the maximum allowable force applied at point C of the shank:

$$R_{Fmax} \leq \frac{b \cdot h^2 \cdot [G]}{6H_1} \, . \tag{13}$$

Substituting the values of the quantities, we obtain: $R_{Fmax} \leq 4291\ N$; 1806 $N <$ 4291 N

The safety factor of the chisel shank according to the flexural resistance criterion is more than 2-fold margin.

Appendix 2

Table 1. Specification of Tractor K-701

Type of machinery	Harrowing, moldboard plowing, and cultivating.
Manufacturer	Peterburgsky Traktorny Zavod
Engine power, kW	220
Dimensions: length/width/height, m	6.82/2.85/3.68
Total weight, kg	11450

Table 2. Specification of Plow PLN 8-40

Type of machinery	Plowing to a depth of up to 30 cm in various soils that are not clogged with rocks, stones, or other obstacles
Manufacturer	Belagromash
Field capacity, ha / h	2.9
Number of furrows	11
Working width, m	2.8
Dimensions: length/width/height, m	4.55/3.91/1.22
Total weight, kg	1025

Table 3. Specification of Cultivator KPE-3.8

Type of machinery	Presowing (up to 16 cm depth) and autumn soil tilling, with up to 50% stubble remaining on the surface
Manufacturer	LesAgroMash, Kirov
Working width, m	3.91
Field capacity, ha / h	2.35-3.50
Dimensions: length/width/height, m	6.55/3.91/0.22
Total weight, kg	1150

Table 4. Specification of Seeder SZU-3.6

Type of machinery	Grain seeder with fertilizer application
Manufacturer	TD Agro-Resurs, Lipetsk
Working width, m	3.6
Field capacity, ha / h	3.2-4.3
Insertion depth, m.	0.4-0.8
Dimensions: length/width/height, m	4300/3700/1650
Total weight, kg	1380

Table 5. Specification of Tractor DT 75

Type of machinery	Crawler agricultural tractor
Manufacturer	Volgogradsky Traktorny Zavod
Engine power, kW	70
Dimensions: length/width/height, m	4.40/1.85/2.71
Total weight, kg	6950

Table 6. Specification of Harvester Yenisei 1200

Type of machinery	Grain harvester
Manufacturer	Krasnoyarsky zavod kombainov
Engine power, kW	103
Total weight, kg	9730
Field capacity, kg / h	9000
Cutter bar width, m	6.5
Grain tank capacity, m^3	4.5

Table 7. Specification of Tractor MTZ-82

Type of machinery	All-wheel drive tractor
Manufacturer	Minsk Tractor Works, Belarus
Engine power, kW	60
Dimensions: length/width/height, m	3.93/1.97/2.78
Total weight, kg	3900

Table 8. Specification of Sprayer ON-600

Type of machinery	Mounted sprayer
Manufacturer	Zarya LLC, Chelyabinsk region
Tank volume, l	600
Processing width, m	12
Total weight, kg	280