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Study of effectiveness of controlled traffic farming system and wide span self-propelled gantry-type machine

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Abstract

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Trends in the global agricultural sector tend to efficient use of resources and improving the quality in agriculture. A significant effect in this regard can be achieved when using controlled traffic farming and wide span self-propelled gantry-type machine. The aim of this study is theoretical justification of the cost-effectiveness of introduction of the controlled traffic farming system and using of wide span self-propelled gantry-type machine, by selecting some optimal parameters of land use. Provided studies have shown that the most significant economic effect of introduction of the controlled traffic farming system is evident on the fields with high anthropogenic degradation of soils, where the results of crop yields increasing due to natural processes of soil decompression will be essential. The economic effect obtained by the implementation of the controlled traffic farming system by saving energy costs and seed. and due to increased crop yields is a minimum at the level of 150 € per ha.

Keywords: precision agriculture; field machine passes; time utilization; reduction of the soil compaction; economic efficiency

A cropping system based on using controlled traffic farming means the separation of machinery traffic areas from plants´ growing zones. In this case, the functionality of the field area is divided into fertile (agrotechnical) area and technology (engineering) area. In practice, this means that one and the same wheel track is used for soil treatment, planting, spraying and harvesting; wheels of mobile power vehicles (tractors) and machines are adjusted to the same track width.

The natural meaning of the controlled traffic farming system is based on a need to solve the fundamental contradictions in the system of "propeller - soil", the essence of which is to achieve high traction properties of tractors having contact with dry and compacted soil, while on the other side there must be ensured optimal soil moisture and loose environment for normal plant growth.

According to Godwin and Miller (2003), western farmers are actively using controlled traffic

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farming, and scientists in Europe and Australia are looking for new solutions in the development of this technology. Along with this, there are new conservative arguments based on the main ideas that due to the establishing tramlines for machines, the size of sowing area naturally decreases. It should be noted that this saves the amount of seeding material. Depending on the field size and width of the tramline area the percentage of allocated engineering zone can vary significantly. From a purely technical point of view, the machines movement in the constant tramline improve their technical and operational performance. It is expressed as a reduction of energy costs for technological processes and an increase of work productivity (Galambošová et al. 2014).

The work along the technology tramline is more simple, the spraying and fertilizing operations are less tiring for the operator, and in the same time the quality of these operations is quite high.

According to Kroulík et al. (2013), GPS navigation used in agricultural machinery in the form of controlled traffic farming system creates a lot of possibilities of environment and soil protection. From a technological point of view, especially topical is the application of controlled traffic farming system in the transition to soil conservation tillage systems, where decompaction of the soil occurs due to natural soil processes and soil compaction is becoming one of the major obstacles in obtaining high crop yields.

In this regard, the transition to the controlled traffic farming system with the use of a wide span self-propelled gantry-type machine eliminates the compaction and destruction of soil by wheels and tracks of the tractors. It allows to ensure the preservation of the natural fertility of the soil in the production field area (Galambošová et al. 2010) and to provide higher yields of grain crops by 10–15%, of industrial crops by 15–20% and of vegetables by 20–35%.

Due to the above circumstances, the question arises how large the economic benefit obtained by using of the controlled traffic farming system can be. And what are the optimal values of land-use indicators to determine the value of maximum economic efficiency at the same time?

Scientists of many countries around the world pay strong attention to the effectiveness of the controlled traffic farming system using on farms; a research carried out in some typical soil conditions in West Australia (Blackwell et al. 2013) confirmed an average increase of the grain crop yields up to 10 % and a decrease of the fuel consumption of mobile machines due to improved smoothness of their movements.

Also, when using controlled traffic farming, a decrease in energy consumption of the working machines can be observed due to reduced rolling resistance and slippage factor when driving on a solid background traces of permanent tramlines, in comparison with their movement on soft soil surface ground.

Results obtained by Blackwell et al. 2004**a,b**, 2013, confirmed that using of controlled traffic farming without ploughing allows to decrease the fuel consumption of tractors by 25%. Research of the scientists from Queensland (Tullberg et al. 2000, 2007, 2013) showed that a decrease of the fuel consumption was 50% when the controlled traffic farming was used on the loamy soils.

From the results published by Webb et al. 2004, it can be seen that the controlled traffic farming increases the efficiency of crop production by reducing the consumption of seeds, fertilizers and herbicides. Using of permanent traffic lines improves performance and trajectory of movement of tractors, as noted in (Bochtis et al. 2010).

Much attention in the scientific literature on this subject is given to soil processes occurring in relation to the controlled traffic farming system use. A research (Evans et al. 2009, 2010, 2011) confirmed that the use of controlled traffic farming and no-till method increases the amount of beneficial microorganisms and macrofauna (worms, ants and termites) in the soil by 40–160%.

Reduction of capital costs and depreciation of tractors when using controlled traffic farming was analysed in details (Isbister et al. 2013).

The latter authors have stated that due to better traction conditions of tractor with the ground in the zone of permanent technological tracks there are lower energy costs. It is possible to use tractors with lower purchase price, which reduces the amount of depreciation and allows using more such tractors during the year on the farm.

Despite the studies of the problems related to this issue, the considered publications, however, do not allow to estimate the economic impact by saving energy costs, seed and by increasing crop yield, which can be obtained due to the controlled traffic farming system implementation in farm conditions.

Moreover, the functional dependence of the economic benefit that can be obtained by introduction

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of the controlled traffic farming on the land use indicators in the planning and organization of the movement of the field wide span machine-tractor unit (gantry) has not been enough studied and analysed by scientists.

MATERIAL AND METHODS

The aim of this study is theoretical justification of the economic effectiveness of implementation of the controlled traffic farming system and wide span self-propelled gantry-type machines, on the basis of selection of the optimal parameters of land use. As study methods there were used the basic laws of economics using PC and the Mathcad packet.

The rapid development of controlled traffic farming in the world in recent years strongly suggests the broad prospects of wide span self-propelled gantry-type machines. In many European countries, including Ukraine, a research was also carried out in this regard, aimed at the development of scientific bases of aggregation wide span vehicles, providing a decrease in energy, material and labour costs in agricultural production.

With the aim of practical implementation of controlled traffic farming, this study created a concept of a wide span self-propelled gantry-type machine, the design of which contains primarily power-trains to drive self-propelled chassis, hydraulic hinge mechanism for the aggregation of agricultural tools, motion control devices of the machine and others (Fig. 1).

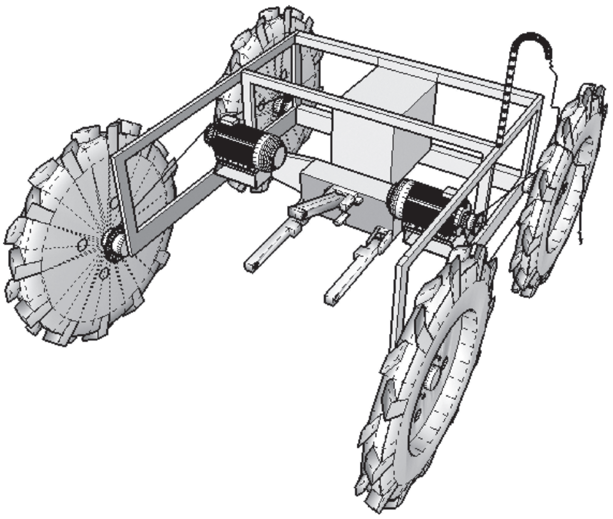

Fig. 1. Design of a wide span vehicle (gantry-type) for the controlled traffic farming realization

(a)

(b)

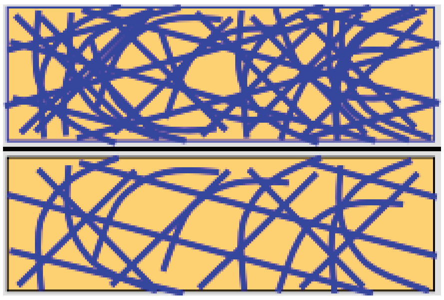

Fig. 2. Deeply compressed wheel tracks, exposed to sheet erosion of topsoil, clearly showing how compaction has affected 80% of this field (Tullberg 2004) (a) and the character of disordered traces of wheeled vehicles on the field (b)

The economic effect of the controlled traffic farming introduction was evaluated by comparing two technologies of cultivation of agricultural crops on the fields having the same geometric shape and acreage.

In one of them, traditional tractor and combine harvester technologies were used in the processes of the soil tillage, seeding, plant care and harvesting. During a year, the machines entered the field from 5 to 25 times. Typically, the total area of the tracks caused by tractor wheels exceeded the field area 1.1–2.0 times, 10–15% of the field was exposed to passes from 6 to 20 times, 65–80% 1–6 times and only 10–18 % of the field area was not affected by the machine passes (Fig. 2).

In view of the above mentioned circumstances, in conventional farming system the soil density increased when compared with the optimal value, both in arable and subarable layers and is ρ_{p1} and ρ_{pp1} (g·cm^{-3}), respectively, which is usually as one of the main reasons of the shortage of the yield U_{f1} (t·ha^{-1}).

According to the methodology, the other technology used was controlled traffic farming. To perform the full range of field operations a single

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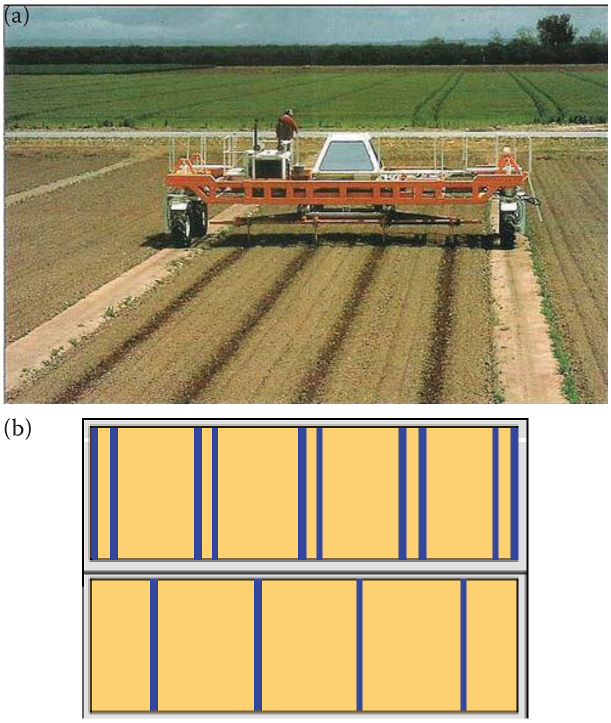

Fig. 3. Controlled traffic farming and wide span self-propelled gantry-type machine (a) and the character of the tramlines of the wheel-type machines on a field (b)

power module was used – self-propelled wide span gantry-type machine, which moves in permanent tramlines (Fig. 3). Coverage of field surface by machine passes was 5–10%.

Due to the lack of compaction impact on the soil caused by wheels of the self-propelled wide span gantry-type machine, in the fertile field zones soil decompression occurs due to natural soil processes. Such farming technology leads to substantial changes in soil bulk density both in arable soil layer ρ_{p2} and also in subsoil layer ρ_{pp2} ($g \cdot cm^{-3}$). In soil, there is a tendency to renew its equilibrium state, which can be close to optimal values, providing a maximum yield ($t \cdot ha^{-1}$) of the grown crops.

The economic effect E obtained from the introduction of the controlled traffic farming system is defined primarily by three components:

$$E = \Delta e_h + \Delta e_s + \Delta e_e \quad (1)$$

where: Δe_h – the economic effect of increasing the yield of growing crop, $€ \cdot ha^{-1}$; Δe_s – economic effect of saving seeding material, $€ \cdot ha^{-1}$; Δe_e – economic effect of saving energy costs, $€ \cdot ha^{-1}$

Let us consider each component of the Eq. (1) separately.

The economic effect Δe_h of the increase of crop yield can be represented as the difference between the values of gross output, obtained at using the two examined farming techniques (Figs 2 and 3):

$$\Delta e_h = \Delta e_{h2} - \Delta e_{h1} \quad (2)$$

where: Δe_{h2} – the value of gross output, obtained by using a controlled traffic farming technology ($€ \cdot ha^{-1}$)

$$e_{h2} = (1 - w_1)U_{f2}V_{h2} \quad (3)$$

where: e_{h1} – the value of gross output, obtained by using a traditional growing technology ($€ \cdot ha^{-1}$)

$$e_{h1} = U_{f1}V_{h1} \quad (4)$$

where: V_{h1}, V_{h2} – the price of 1 t of the crop yield obtained using the two farming technologies ($€ \cdot t^{-1}$), U_{f1}, U_{f2} – actual yields of the cultivated crops, grown according to the two farming technologies ($t \cdot ha^{-1}$); w_i – losses of the field surface used as an engineering area

RESULTS AND DISCUSSION

The methods allowing to express the soil compaction effects of the passes of field machines and tractors with regard to economic consequences of the perspective farming technologies in crop production are well known.

The methods of dynamic programming make it possible to compare the technological attributes of local resources and they determine the level of impact of anthropogenic activities on the soil and give an economic evaluation of both the developed and implemented technologies of crop growing as well as of the entire technological and technical tillage systems.

As a basis of the above-mentioned methods the results obtained by Rusanov (1998) were considered. According to his research, the predicted change of yield of the growing crop depends upon bulk density of the soil, both in its arable and subarable layers:

$$U_f = U_{max}(1 - ((C_p|\rho_p - \rho_0|K_p)^n + (C_{pp}|\rho_{pp} - \rho_0|K_{pp})^n)) \quad (5)$$

where: U_f – real yield of the growing crop obtained in conditions of the soil bulk density in arable soil layer (0–20 cm) ρ_p, and subarable layer (20–40 cm) ρ_{pp} ($t \cdot ha^{-1}$); U_{max} – maximal yield of the field crop obtained in case of the optimal soil bulk density ρ_0 ($t \cdot ha^{-1}$); C_p, C_{pp} – empirical coefficients ($cm^3 \cdot g^{-1}$); n – exponent; K_p, K_{pp} – coefficients of recovery of the soil bulk density in arable layer and subarable layer

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With regard to the above-mentioned farming technologies, the Eq. (5), respectively, takes the form:

$$U_{f1} = U_{\max}(1 - ((C_{p1}|\rho_{p1} - \rho_0|K_{p1})^n + (C_{pp1}|\rho_{pp1} - \rho_0|K_{pp1})^n)),$$

$$U_{f2} = U_{\max}(1 - ((C_{p2}|\rho_{p2} - \rho_0|K_{p2})^n + (C_{pp2}|\rho_{pp2} - \rho_0|K_{pp1})^n)) \quad (6)$$

Taking into account Eq. (3–6) the Eq. (2) takes the form:

$$\Delta e_h = (1 - w_i)U_{\max}\left(1 - \left(\left(C_{p2}\left|\rho_{p2} - \rho_0\right|K_{p2}\right)^n + \left(C_{pp2}\left|\rho_{pp2} - \rho_0\right|K_{pp2}\right)^n\right)\right)$$
$$V_{h2} - U_{\max}\left(1 - \left(\left(C_{p1}\left|\rho_{p1} - \rho_0\right|K_{p1}\right)^n + \left(C_{pp1}\left|\rho_{pp1} - \rho_0\right|K_{pp1}\right)^n\right)\right)V_{h1} \quad (7)$$

The economic effect Δe_s can be presented as the difference in the costs of seeding material required for the two variants of the farming technologies:

$$\Delta e_s = e_{s1} - e_{s2} \quad (8)$$

where: e_{s1} – price of the seeding material used for the traditional farming technology (€·ha^{-1})

$$e_{s1} = u_s V_s \quad (9)$$

where: e_{s2} – price of the seeding material used for the technology of controlled traffic farming (€·ha^{-1})

$$e_{s2} = u_s V_s(1-w_i) \quad (10)$$

where: u_s – standard seeding rate for seeding of the given growing crop (t·ha^{-1}); V_s – price of the seeding material (€·t^{-1})

With regard to (9) and (10), the equation (8) takes the form:

$$\Delta e_s = u_s V_s w_i \quad (11)$$

Let us justify the effect Δe_s of saving energy costs due to the implementation of the controlled traffic farming technology. Reducing energy consumption is due to two components: the reduction of working resistance of the tillage implements and reduction of the costs connected with movement of the wide span self-propelled gantry-type machine, whose wheels interact with the compacted soil tramlines track.

Based on the results obtained in many research activities focused on wide span self-propelled gantry-type machines, it can be stated that the decrease of the fuel consumption related to 1 ha can reach the value of 10% and even more (Blackwell et al. 2004, 2013; Tullberg et al. 2000, 2007, 2013).

The considered computational procedure allows to estimate the value E related to implementation of the controlled traffic farming system, taking into account the level of exposure to anthropogenic activities on the soil by using a generalized indicator of the soil bulk density. The indicator of soil bulk density can be considered as a factor of yield of the growing crop.

As an argument of the studied function (1), the indicator w_i of the rate of loss of the field area (in relative units) used as an engineering field area was considered.

The value of the soil bulk density in studied crop-growing technologies, as mentioned before, will determine the level of crop yield productivity and, consequently, the price of gross output.

Therefore, there was examined the nature of the change of the desired function E of the absolute difference of soil bulk density as a result of its decompaction due to natural soil processes during the transition to the controlled traffic farming system. In this case, it was assumed that both in arable and subarable soil layers the difference of the soil bulk density would be identical

$$\Delta\rho = \rho_{p1} - \rho_{p2} = \rho_{pp1} - \rho_{pp2}$$

To calculate the value of the economic effect E of the controlled traffic farming system implementation, the following values of parameters were used on the example of wheat growing in Europe (Table 1).

The results of evaluating the effectiveness of controlled traffic farming in relation to the saved energy costs, seeding material, and increasing the yield of wheat grain according to (1) are shown in Fig. 4.

Analysis of the Fig. 4 shows that the economic benefits that can be obtained by the implementation of controlled traffic farming are directly determined by the losses of the field area under the engineering area w_i designed to move a wide span gantry-type machine and other means of mechanization, and may also place additional communication. The effectiveness of the field planning and management and organization

Table 1. Indicators of the wheat growing in Europe

Indicator	Unit	Value
Yield of the wheat grain	t·ha^{-1}	7.5
Price of the wheat grain	€·t^{-1}	130
Standard of a wheat seeding rate	t·ha^{-1}	0.14
Price of the wheat for seeding	€·t^{-1}	460
Price of the diesel fuel	€·kg^{-1}	1.36

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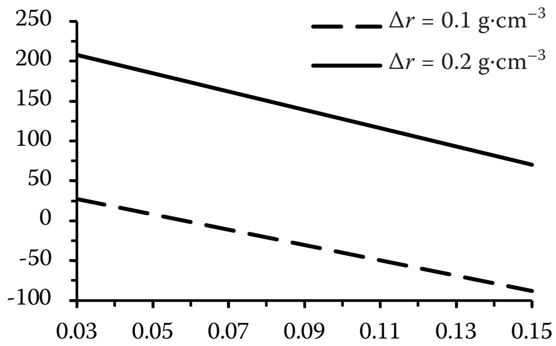

Fig. 4. The results of evaluating the effectiveness of the controlled traffic farming in relation to saved energy costs, seeding material, and increasing the yield of wheat grain for different values of the soil decompaction Δρ: 1 – Δρ = 0.1 g·cm^{-3}, 2 – Δρ = 0.2 g·cm^{-3}

of movement of a self-propelled wide span gantry-type machine will significantly affect the economic performance and controlled traffic farming.

If the loss of the field area used as an engineering area of the controlled traffic farming reach more than 6% and the absolute value of the natural soil decompaction is only Δρ = 0.1 g·cm^{-3}, it would be impossible to obtain a positive economic effect only due to the yield increase (curve 1, Fig. 4).

According to our results related to losses of the used area of the field, it is possible to reach the losses of the used area of the field lower than 6% if the wide span gantry-type machine with the width of the tracks at least 8-10 m is used. In this case, the income from gross production will not be less than in traditional agricultural technology at least. Such parameters are currently typical for the experimental wide span self-propelled gantry-type machines, for example ASA-Lift WS 9600 WS (ASA-Lift, Denmark) with the width of tracks 9.6 m (Pedersen et al. 2013).

More significant economic benefits of the controlled traffic farming use will be evident in the case when the soil compaction will become a main obstacle to reach high yields of the field crops in the traditional farming technology.

And, if in the conditions of the correct conservation agriculture using the controlled traffic farming the value of the natural soil decompaction is reached at the level Δρ = 0.2 g·cm^{-3}, the economic effect due to a significant yield increase will be evident, even with the losses of the field area under the engineering area being 15% (curve 2, Fig. 4).

The value of the economic effect will be greater in the case when a part of the field area allocated as an engineering area will be smaller. When using the above-mentioned wide span gantry-type machine ASA-Lift WS 9600 WS, the economic benefit of savings of energy costs and seeding material, and increasing of yield of wheat will be a minimum of 150 € per each hectare where the wheat is grown.

CONCLUSION

Studies have shown that the economic benefits that can be obtained due to implementation of the controlled traffic farming system are directly determined by the losses of the field area used as an engineering area designed to support the moving of a wide span gantry-type machine and other means of mechanization, and may also place additional communications.

The management of field operations and organization of the movement of the wide span gantry-type machine and other means of mechanization will significantly affect the economic indicators of the controlled traffic farming system.

The most significant economic effect of the controlled traffic farming will be evident on the fields with high anthropogenic degradation of the soil, where the result of crops yield increase due to natural processes of soil decompaction will be essential.

The economic effect of the controlled traffic farming allowing to save energy costs, seed and to increase the yield of grown crops by using modern models of self-propelled wide span gantry-type machine, related to growing of wheat, is a minimum of 150 € per hectare according to our results. It allows to pay investments for a promising new precision farming technologies.

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