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Physical and mechanical properties of soil for ridge formation, ridge geometry and yield in new planting and ridge formation methods of potato production

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In 2008 and 2009, a trial was performed to enhance the physical and mechanical properties of light soil for ridge formation, to increase the cross-sectional area of loose soil in the ridge, to improve the marketable yield and time efficiency, and to lower the percentage of green tubers. Three different planting and ridge formation methods applied to potato production were compared. The first method involved simultaneous planting and small ridge formation, followed by final ridge formation with a PTO-driven potato cultivator immediately before potato emergence (CL method). The second method combined planting and simultaneous final ridge formation (P+FR method), while, in the third method (BF+P+FR method), a special bed former attached to the front of a tractor that pushed the loose soil off the tractor wheels was used. The trial design was a randomised complete block with three repetitions. The BF+P+FR method produced the best physical and mechanical properties of the soil for ridge formation, while the CL method produced the poorest. Due to greater distance of the seed tuber from the ridge centre, the CL method resulted in the largest yield and percentage of green tubers. In comparison with the other two methods, the CL method gave a lower percentage of marketable tubers and a higher percentage of non-marketable tubers. Moreover, the BF+P+FR and P+FR methods were more time-efficient during planting and ridge formation than the CL method.

Keywords: green tubers; potato; ridge formation; soil properties; yield

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Introduction

In potato production, special emphasis needs to be placed on soil protection, particularly on retaining good soil structure and reducing soil compaction by decreasing the frequency of tractor passes through the same track of land (VDI 2007). This needs to be considered in the process of soil preparation as well as during planting and ridge formation.

In practice, relatively successful technical solutions for simultaneous potato planting and final ridge formation have been established (Peters 2009). A German potato producer Andreas Heiss developed and produced a combined machine intended for simultaneous soil preparation, planting and final ridge formation (Schmid 2009). In contrast, the classic method requires at least two passes through the same track of land for planting and final ridge formation. Cultivation and ridge formation are usually performed two weeks to one month after planting. This method uses a tractor with narrow tyres which causes a high level of compaction of the inter-row space. It is especially unadvisable to drive through finely cultivated or extremely wet soil because this practice seriously affects the soil's fertility and structure and results in lower yields (Sommer and Zach 1986). Soil compaction is closely linked with the physical properties of the soil, soil density, porosity and vertical penetration resistance (Sommer *et al.* 1976).

Field trials performed on sandy loam by Sommer *et al.* (1976) with different tractor tyres showed a reduction of porosity from 47–51% to 41–43% at a wheel load of 1000 daN. Furthermore, the porosity of the soil which had not yet been driven over was significantly higher than the porosity of the soil that had been crossed two to six times (Sommer, Ruhm and Altenmüller 1981).

A power take off (PTO)-driven cultivator cultivates only half of an entire inter-row width. Furthermore, it predominantly cultivates tyre tracks made by the tractor during planting and cultivation as well as tyre tracks made by the planter and cultivator. It is unable to crush the clods formed at the ridge top during planting and those on its sides. The main part of the ridge, thus, remains uncultivated. The clods that are formed during the process of soil preparation become especially problematic at harvest time. If the harvest takes place in humid conditions, a high percentage of small aggregates in the ridge (<3 mm) result in the creation of new clods (Kouwenhoven and Perdok 2000). In the later process of inter-row cultivation, a higher vertical penetration resistance was measured in the upper 15 cm of the soil when compared with cultivation with a combined machine for simultaneous planting and final ridge formation (Heiss 2009). In addition, Isensee (1986) determined that each tractor pass increases the vertical penetration resistance by the depth, which, in turn, gradually deepens the tyre tracks.

Due to a lengthy spring drought in the period after planting according to the classic method (where planting and final ridge formation are performed separately), light soil becomes structurally unstable in the ridging period, thus, rendering ridge formation impossible. From the economic and practical points of view, simultaneous work during a single tractor pass offers an advantage in potato production (Peters 2009). Moreover, this author established that, in comparison with ridge formation 2 weeks after planting, soil erosion was less pronounced with simultaneous planting and final ridge formation.

Potato requires well loosened soil and a ridge of a stable form and height (Kouwenhoven 1978). For proper plant emergence, the soil in the ridge must be loose and contain soil particles that do not exceed 6 mm in diameter because this allows a better transfer of water and heat. The latter enables speedy potato emergence and good plant growth; furthermore, it simplifies the subsequent potato harvest (Kouwenhoven *et al.* 2003). The frequency of passes through the same track of land, the tyre type and any soil compaction during soil preparation and ridging are the most influential factors affecting the percentage of clods in the ridge. Tyres compact the soil on the sides of the ridge and weigh down upon the tubers directly or indirectly through clods and rocks (Peters 1999).

Ridge size is important in terms of soil cover of tubers. Kouwenhoven and Perdok (2000) define the ridge size as the cross-sectional area of loose soil in the ridge during pre-planting, soil preparation and ridging. Gerighausen (1994) determined that, at the 75 cm inter-row width (IRW), the cross-sectional area should be between 900 and 1000 cm^2. During the period of growth, the cross-sectional area of the ridge was reduced by 15–20%, with the angle of the ridge side being reduced from 45° to 40° (Kouwenhoven 1978). In smaller ridges, the majority of tubers grow near to the surface of the cross-sectional area of the ridge thus increasing the possible occurrence of green tubers (Struik and Wiersema 1999). An increase in the cross-sectional area of the ridge at greater IRW results in a reduction of the horizontal span of tubers and lowers the percentage of green tubers.

Heiss (2009) determined that the use of PTO-driven cultivators was linked with a lower quality of tubers and yield reduction as well as with a higher percentage of green tubers, damaged tubers and insufficiently large tubers. When a combined machine was used, the percentage of green tubers was the lowest among the different potato planting and ridge formation methods (3.2%). In contrast, the percentage of green tubers with a PTO-driven cultivator at the 90 cm IRW reached 8.7% (Heiss 2009). If the method of simultaneous planting and final ridge formation is applied, seed tubers are positioned at the ridge centre. This location, however, does not occur if final ridge formation is performed at a later point, particularly on a tilted terrain.

The objective of the study was to determine the most appropriate planting and ridge formation method for improving the physical and mechanical properties of soil for ridge formation, increasing the cross-sectional area of loose soil in the ridge, increasing marketable yields, improving the time efficiency and lowering the percentage of green tubers. In the trial, three different planting and ridge formation methods were compared. The first method involved simultaneous planting and small ridge formation, followed by final ridge formation with a PTO-driven potato cultivator immediately before potato emergence (CL method). The second method combined planting and simultaneous final ridge formation (P+FR method), while, in the third method (BF+P+FR method), a special bed former attached to the front of a tractor that pushed the loose soil off the tractor wheels was used. Our hypothesis was that, in comparison with the other two methods, the BF+P+FR method would give better physical and mechanical properties of the soil for ridge formation. Compared to the CL method, the P+FR and BF+P+FR methods were expected to result in an increased cross-sectional area of loose soil in the ridge, net cross-sectional area of loose soil in the ridge, marketable yield, percentage of marketable yield and time efficiency, with a decreased green tuber yield and percentage of green tubers.

Materials and Methods

Trial base

The trial was performed on light soil in Dol pri Ljubljani (46°04′ N, 14°31′ E; Slovenia) during 2008 and 2009. The soil was classified as loam (I) containing 10.1 and 8.3% of clay (Table 1). The trial design consisted of randomised blocks with three repetitions. In each block, three different potato planting and ridge formation methods were randomly applied. Blocks were 5 m long and 13.5 m wide. Between the blocks, there were 10 m passages to facilitate the turns of the tractor, planter and ridger. Each treatment consisted of 6 rows of potato with a 75 cm IRW. The area of a trial plot for individual treatments was 22.5 m^2 (5 m long and 4.5 m wide). All the measurements were performed in the two inner rows. The planting density was 45,000 tubers per hectare, with a 29.6 cm distance among tubers in a row. In the trial, 'Aladin', a medium-to-late potato cultivar (35–55 mm), was used. Data on basic fertilisation, soil preparation and planting are provided in Table 2. Other agro-technical procedures were performed in accordance with good agricultural practice.

Table 1. Soil texture in Dol pri Ljubljani in 2008 and 2009

Year	2008	2009
Sand (%)	47.7	45.6
Silt (%)	42.2	46.1
Clay (%)	10.1	8.3
Texture class	I (loam)	I (loam)

Planters and ridgers for potato production

In the trial, three different planting and ridging methods for potato production were used. The first method was the classic method (CL) (Figures 1a and 2a), which consisted of planting with an automatic potato planter with ridge discs for the formation of small ridges. In this method, the seed tuber is covered with a thin layer of soil that allows speedy potato emergence. Immediately before or after emergence, cultivation with the PTO-driven cultivator/ridger is performed (Biotechnical Faculty, Department of Agronomy, Ljubljana, Slovenia), which was described in detail by Bernik and Vučajnk (2008).

The second method consisted of simultaneous planting with an automatic planter and final formation of trapezium-shaped ridges with an attached ridger (Biotechnical Faculty, Department of Agronomy, Ljubljana, Slovenia) (P+FR). This machine is a remodelled version of an existing automatic potato planter with some additional elements (Figures 1b and 2b). In the front part of the planter there is a mount for elastic tines that loosen the soil behind the wheels of the tractor. The height of the mount can be adjusted. Special side guards on each side of the mount prevent the soil from falling into the inter-row space. Attached to

Table 2. Agro-technical procedures

Agro-technical sequential work	Year	
	2008	2009
1. Manure spreading, 30 t/ha	Oct. 2007	Oct. 2008
2. Ploughing with 2-furrow reversible plough	Oct. 2007	Oct. 2008
3. Basic mineral fertilisation with a 2 disc spreader	7/5/2008	6/4/2009
4. Soil preparation with a rotary harrow	8/5/2008	7/4/2009
4.1. Rotor speed of rotary harrow (rpm)	300	300
5. Simultaneous planting and final ridge formation	9/5/2008	8/4/2009
6. Cultivation and ridge formation with a PTO-driven cultivator	2/6/2008	4/5/2009
6.1. Rotor speed of the PTO-driven cultivator (rpm)	240	240

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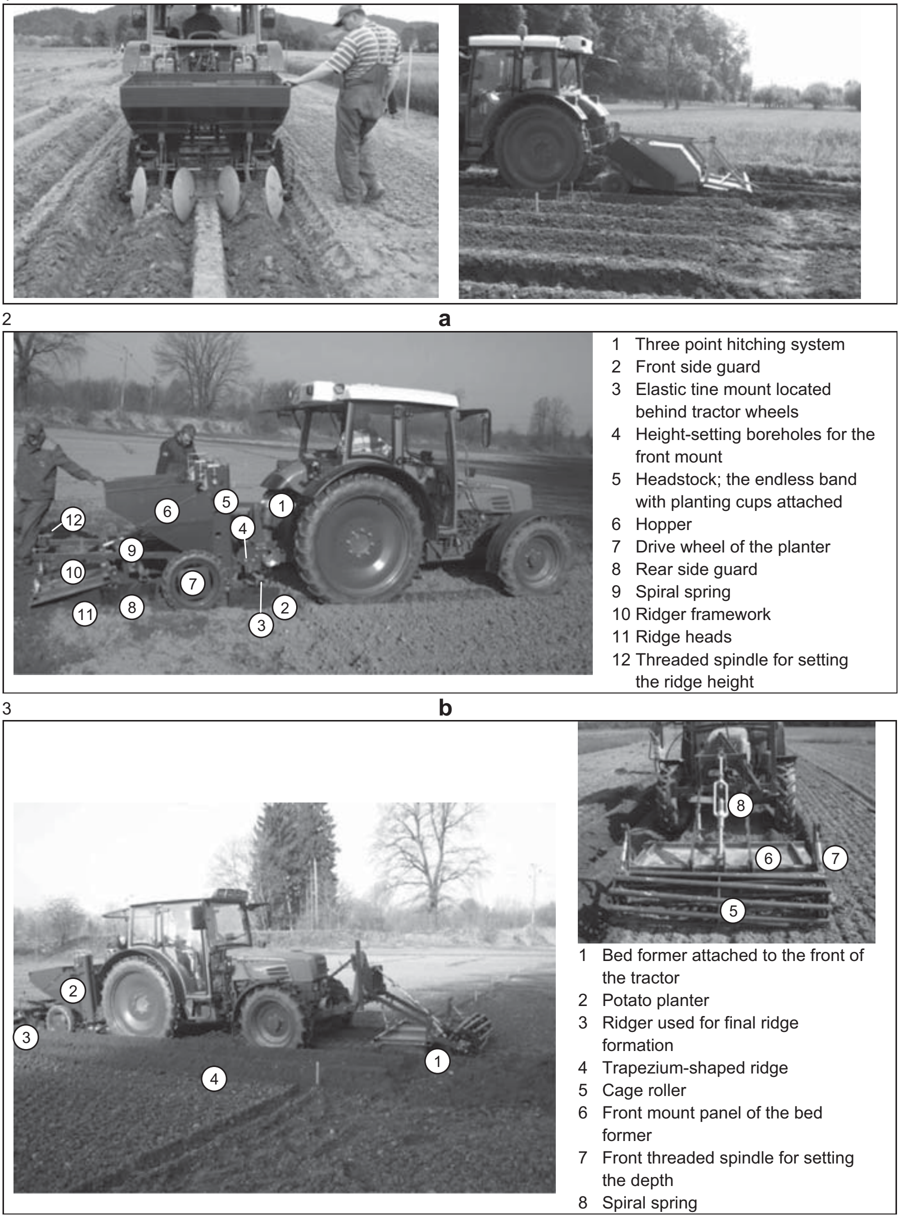

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Figure 1. (a) the CL method consisted of a potato planter with a ridger for the formation of small ridges and a PTO-driven cultivator/ridger to be used before potato emergence; (b) the P+FR method consisted of a potato planter with a ridger for final ridge formation; (c) the BF+P+FR method: potato planter with a ridger for final ridge formation, and a special bed former attached to the front of the tractor pushing the loose soil for ridge formation off the wheels of the tractor.

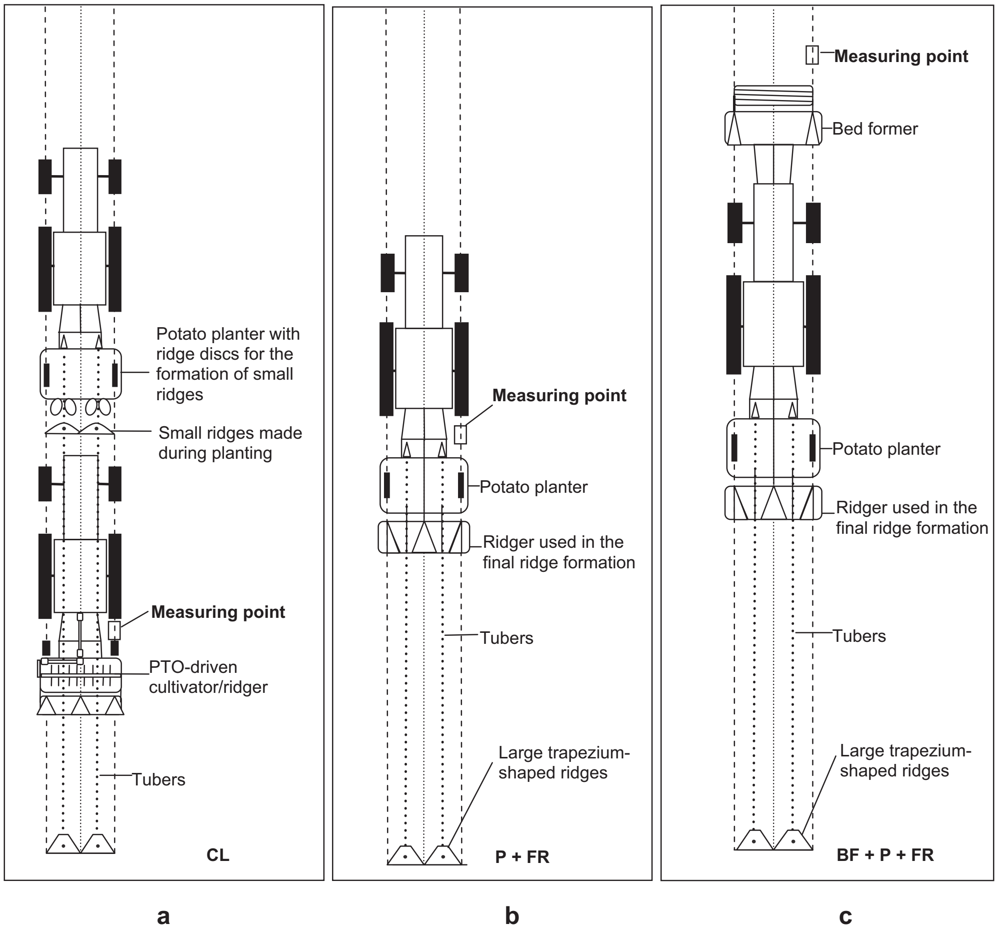


Figure 2. Diagram of planting and ridge formation according to the CL (a), P+FR (b) and BF+P+FR (c) methods with the relevant measuring points.

the rear side of the planter, a ridger with large ridge heads forms trapezium-shaped ridges. Fixed upon the framework of the ridger, two side guards redirect the soil from the side towards the inner part of the ridger. If needed, a single tine or a couple of elastic tines loosening the planter's tracks might be attached to the mount behind the planter's tyres.

The third planting and ridge formation method consisted of a special bed former attached to the front three-point hitching system of a tractor (BF+P+FR). The bed former ridger (Biotechnical Faculty, Department of Agronomy, Ljubljana, Slovenia) pushes the soil in front of the wheels aside, onto the bed, thus preventing the wheels from compacting the soil destined for ridge formation (Figures 1c and 2c). The bed former ridger is attached to the front part of the tractor via the hitching triangle. An automatic potato planter with a ridger for final ridge formation as described in the previous method is attached to the rear three-point hitching system of the tractor. All the described machines came in a two-row version.

Before the planting began, 17 tubers per row had been manually placed into planting cups of the planter attached to an endless band. On a 5-metre long plot, 17 tubers were planted in a row at a distance of 30 cm, which amounted to a total 45,000 tubers per hectare. During the planting, the gearbox of the automatic potato planter was set at a suitable ratio to get the desired intra-row spacing of tubers (30 cm). Thus, we managed to prevent possible double intake of tubers and the occurrence of gaps among tubers. A tractor with narrow tyres and a rated power of 60 kW was used in the trial. It had tubeless radial tyres 230/95 R 40 (9.5 R 40) with 1.6 bar tyre inflation pressure. Radial tyres 9.5 R 24 with 1.6 bar of tyre inflation pressure were attached to its front drive shaft. The tractor's wheel spacing was 149.4 cm in the front and 150 cm in the rear. Unladen weight of the tractor was 3300 kg.

Measurements of the physical and mechanical properties of the soil

Measurements of physical and mechanical properties were performed on the soil that was driven over by tractor wheels during planting and ridge formation, and intended for final ridge formation (Figure 2). The tractor with its attached machine came to a halt at the end of a trial plot. A metal frame (50×25 cm), within which measurements were performed was put behind its wheel. In the BF+P+FR method, the frame was placed in front of the front bed former, because the latter pushes the soil off the wheels of the tractor. Thus, the wheels of the tractor do not run over the soil intended for ridge formation (Figure 2c).

At first, the vertical penetration resistance was measured with a self-constructed hydraulic penetrometer with a tip that had an angle of 30° and an area of 1.29 cm^2, in accordance with the ASAE S313.1 standard (Chancellor 1994). The penetration speed of the tip going into the soil was 1.83 m/min, which equals to 3.05 cm/s. A detailed description of the above-mentioned penetrometer is available in Bernik and Vučajnk (2008). The Lab View program (National Instruments, Texas, USA) allowed us to gather and partially process the data obtained during the measurements of vertical penetration resistance. At individual measuring points, the measurements of vertical penetration resistance were performed up to a depth of 25 cm. Each measuring point involved 5 measurements. Data processing involved the analysis of an average vertical penetration resistance 0–25 cm of depth. Moreover, the vertical penetration resistance was calculated according to individual depths for the three potato planting and ridge formation methods.

Subsequently, soil samples were taken from the same measuring points up to a depth of 10 cm with a Kopecky cylinder with a 100 cm^3 volume. A sample was taken from each treatment on an individual block; then the samples were weighed and allowed to dry for 24 hours at a temperature of 105 °C. After drying, the samples were reweighed. Based on measurement data, soil density, porosity and soil water content were calculated.

At each measuring point, a soil sample was taken up to a depth of 20 cm with a special spade. The sample was passed through sieves with meshes of 50-30-10-5-3-1-0.5 mm (Vučić 1971). After sieving, the samples of individual fractions were weighed and the percentage of soil particles smaller than 10 mm was calculated. Based on the mass of soil particles of an individual fraction, the mean diameter of soil particles of an individual fraction and the total mass of all the fractions, the mean weight diameter (MWD) was calculated.

Ridge shape and distance of the seed tuber from the ridge centre

A three-dimensional coordinate measuring device was used to measure the ridge shape and the position of the seed tuber. The device enables the absolute and relative measurement of distance within the following range: 1000 mm in transverse direction, 450 mm in the longitudinal direction, 600 mm in the vertical direction, to within ±0.5 mm for all directions (Bernik and Vučajnk 2008). The measurements of ridge shape and position of the seed tuber were performed with the LabView computer program (National Instruments, Texas, USA) immediately after ridge formation. The measuring tip was led transversely over the ridge and, at a later point, over the seed tuber. During the process, the measuring point coordinates of the ridge and position of the seed tuber (x,y) were registered with 20 Hz measuring frequency, saving 20 measuring point coordinates per second. Based on the measuring point coordinates of the ridge and the position of the seed tuber, the cross-sectional area of loose soil in the ridge, the net cross-sectional area of loose soil and distance of the seed tuber from the ridge centre were then calculated with the C# Sharp computer program (Figures 3, 4 and 5). C# Sharp is a multi-paradigm programming language which was developed by Microsoft within its .NET initiative (Microsoft Redmond Campus, Redmond, Washington, USA). The net cross-sectional area of loose soil represents the cross-sectional area of cultivated soil between the lower side of the seed tuber and the ridge top. C# Sharp automatically calculates the cross-sectional area of loose soil in the ridge and the net cross-sectional area of loose soil by following the principle of the Gaussian quadrature. The latter is the principle of numerical integral calculus applied with adjacent points of unequal distance. It is based on the sum of individual areas between two adjacent points. In addition to the cross-sectional area of the ridge, C# Sharp calculates the distance of the centre of the seed tuber from the ridge centre on the basis of measuring point coordinates of the ridge and the position of the seed tuber. After calculation, the results and graphs of the cross-sectional area of the ridge, the net cross-sectional area of the ridge and the distance of the seed tuber from the ridge centre were saved in a Microsoft Excel file according to individual measuring points.

Green tubers

Before potato harvest, green tubers were collected from a sample of 10 plants in the 3rd and 4th rows. Each green tuber was weighed, and its thickness was determined with a callipers. Based on the mass of green tubers, the yield of green tubers >40 mm per hectare was calculated. The percentage of green tubers larger than 40 mm in the total tuber yield was calculated.

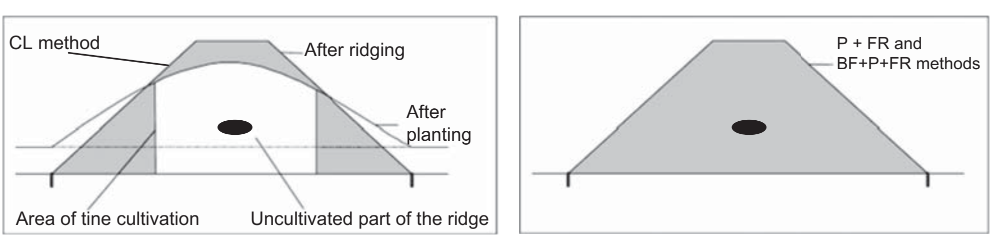


Figure 3. Cross-sectional area of loose soil in the ridge according to the CL, P+FR and BF + P + FR methods.

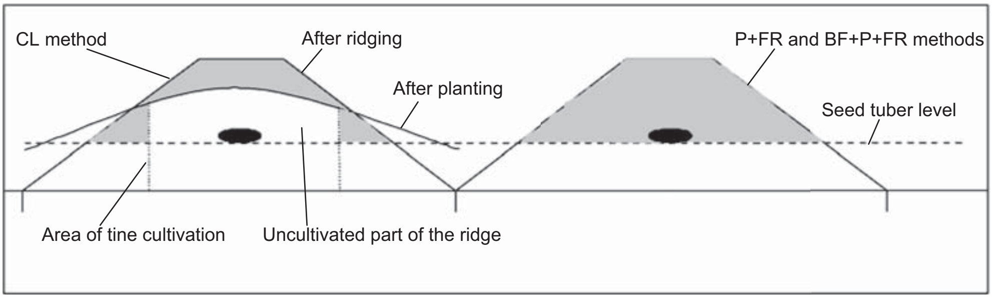


Figure 4. Net cross-sectional area of loose soil in the ridge according to the CL, P+FR and BF+P+FR methods.

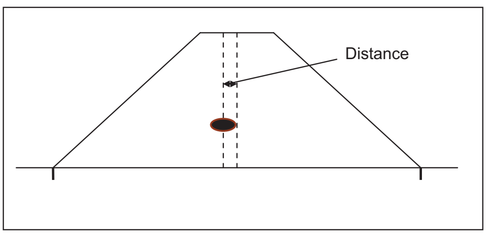


Figure 5. Distance of the seed tuber from the ridge centre.

Marketable and non-marketable yields
In each individual plot, tubers were collected from a sample of 10 plants and placed onto a sieve with a 40 mm mesh. Tubers larger than 40 mm and those smaller than 40 mm were weighed. Subsequently, the marketable yield (>40 mm) and the non-marketable yield were calculated. The non-marketable yield consisted of tubers smaller than 40 mm and the total amount of green tubers (both >40 mm and <40 mm). On the basis of these data, the percentage of marketable and non-marketable tubers was calculated.

Theoretical time efficiency
The theoretical time efficiency was calculated for the three planting and ridge formation methods of potato production. A 30% reduction of efficiency was considered due to the filling of the hopper and turns of the tractor at the end of the field. A two-row machine with a 75 cm IWR was exclusively used in the trial. The planting driving speed was 4 km/h. A two-row PTO-driven cultivator/ridger with a driving speed of 4 km/h was used for the cultivation and final ridge formation. There was a 15% reduction of efficiency due to the turns of the tractor at the end of the field. That cultivation and ridge formation were performed in a single tractor pass was taken into consideration.

Statistical data processing
The statistical analysis was performed with Statgraphics Plus (2000) according to a randomised block design with one factor. First, homogeneity of variance was determined. In the case of non-homogeneity, the data were transformed. Percentage data were transformed using the "asin (sqrt/100)" function. As the trial involved three treatments, an analysis of variance and a LSD Multiple Range Test were performed, where $\alpha=0.05$. A statistical difference was considered significant if $P<0.05$. Differences among treatments are indicated with different supersripts. Data are presented in the tables as means±s.e. Data on vertical penetration resistance were analysed in accordance with the rules

applicable to random blocks with repetitions within the trial units. Each trial point involved 5 measurements. In the statistical analysis, the measured values were used as individual values (repetitions).

In the CL method, final ridge formation was performed immediately before potato emergence, i.e. approximately one month after planting. During this process, the wheels of the tractor and ridger are usually not placed at the exact centre of the inter-row space but slightly to the left or to the right. After ridging, the seed tuber is not positioned in the exact centre of the ridge. Since tubers subsequently grow closer to ridge sides, there is a greater chance of greening. Hence, we wanted to determine the relationship between the percentage of green tubers >40 mm and the distance of the seed tuber from the ridge centre. This relationship was examined using a second order polynomial regression model. In the model, the data of both variables were analysed for both trial years as a whole. The analysis was performed in accordance with the requisites of the procedure. Estimates were calculated for individual parameters within the model and an analysis of variance was performed. Furthermore, the F-statistic, the coefficient of determination, the standard error of the regression and the predicted values were calculated.

Results and Discussion

Physical and mechanical properties of the soil for ridge formation

Vertical penetration resistance: In both trial years, there were statistically significant differences ($P<0.05$) in the vertical penetration resistance between the three potato planting and ridge formation methods. The average vertical penetration resistance was significantly lower in the BF+P+FR method compared to the other two methods and significantly higher in the CL method compared to the other two methods (Table 3). The results for the CL method occurred due to a higher frequency of tractor passes through the same track of land, with two of them occurring during planting and another two during the ridging of the inter-row space

Table 3. Effect of planting and ridge formation methods on vertical penetration resistance (VPR), soil density (SD), porosity (P), soil water content (SWC), mean weight diameter (MWD) and percentage of soil particles <10 mm (SP<10 mm) in the years 2008 and 2009 (LSD Test $\alpha=0.05$). Values are presented as means ± s.e.

Year	Planting and ridge formation method	VPR (N/cm^2)	SD (g/cm^3)	P (%)	SWC (%)	MWD (mm)	SP<10 mm (%)
2008	CL	134 ± 5.6^a	1.68 ± 0.03^a	36.6 ± 1.1^a	22.1 ± 0.3^a	34.6 ± 1.9^a	26.7 ± 2.0^a
	P+FR	81 ± 2.1^b	1.59 ± 0.02^b	40.2 ± 0.7^b	26.7 ± 0.4^b	14.8 ± 1.2^b	60.7 ± 5.5^b
	BF+P+FR	29 ± 1.0^c	1.25 ± 0.04^c	52.8 ± 1.5^c	25.3 ± 0.5^c	8.9 ± 0.4^c	77.8 ± 2.6^c
2009	CL	143 ± 5.5^a	1.61 ± 0.01^a	36.5 ± 0.3^a	27.3 ± 0.7^a	40.7 ± 3.1^a	18.9 ± 5.8^a
	P+FR	77 ± 2.9^b	1.52 ± 0.03^b	42.5 ± 1.3^b	26.5 ± 0.7^a	23.1 ± 2.0^b	39.5 ± 3.9^b
	BF+P+FR	27 ± 1.2^c	1.36 ± 0.01^c	47.5 ± 1.6^c	25.4 ± 0.4^a	11.8 ± 1.1^c	63.2 ± 4.0^c

[abc] Means within a column for a given year without a common superscript are significantly different ($P<0.05$).

CL=classic method.

P+FR=planting and final ridge formation method.

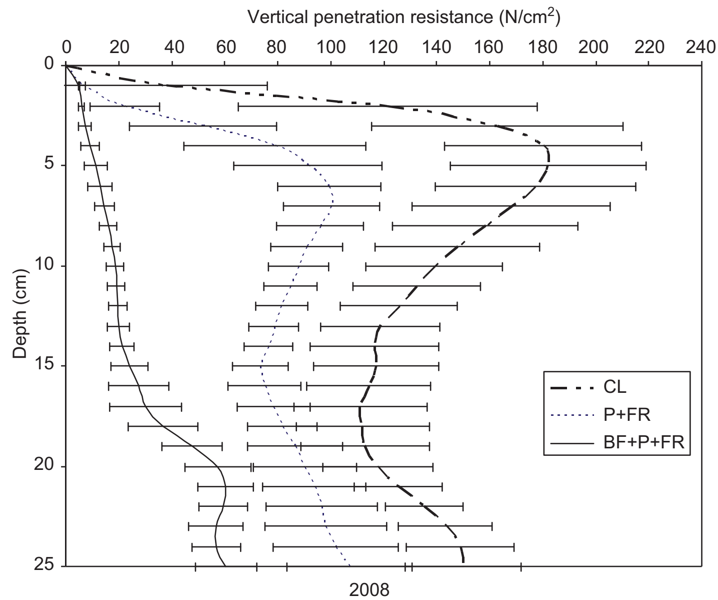
BF+P+FR=bed formation, planting and final ridge formation method.

and ridge formation immediately before potato emergence. The BF+P+FR method included a special bed former attached to the front three-point hitching system of the tractor, which pushes the loose soil in front of its wheels onto the bed, thus preventing the soil from being driven over by tractor wheels. Thus, almost all of the soil in the inter-row space intended for ridge formation remains intact. Soil for ridge formation is driven over twice in the P+FR method, causing the vertical penetration resistance to rank between the other two methods. In both trial years, the vertical penetration resistance of this method was significantly higher than that of the BF+P+FR method and significantly lower than with the CL method. Our results are in agreement with the findings of Sommer and Zach (1986) who found that multiple tractor passes through the same track of land cause an increase in vertical penetration resistance.

When comparing the vertical penetration resistance at individual depths, the BF+P+FR method had a significantly lower vertical resistance at all the depths compared to the other two methods, vertical resistance increased slightly down to a depth of 15 cm, with a greater increase at deeper layers (Figure 6). The highest value was reached at a depth of 25 cm. The CL method had a significantly higher vertical penetration resistance at all depths among the three planting and ridge formation methods, reaching a maximum at a depth of approximately 5 cm, decreasing down to a depth of 18 cm and increasing again to a depth of 25 cm. At all the measured depths, the vertical penetration resistance in the P+FR method was significantly higher than that of the BF+P+FR method, while it was significantly lower than the values of the CL method. Heiss (2009) found that a lower vertical penetration resistance was achieved with the use of a combined machine for simultaneous soil preparation, planting and ridge formation, especially in comparison with the classic method where planting and ridge formation were performed separately in two different periods. When the combined machine was used, the vertical penetration resistance showed a linear increase from 40 to 80 N/cm^2 at depths between 0 and 10 cm, while it was much higher in the CL method, where, at the same depth range, it exceeded a value of 110 N/cm^2.

Soil density

In both trial years, there were statistically significant differences ($P<0.05$) in soil density among the three planting and ridge formation methods. The soil used for ridge formation in the CL method had significantly higher density compared to the two other methods (Table 3). This result was expected because in this method, the soil is driven over 4 times: twice at the time of planting and twice during ridge formation, approximately a month after planting. In the BF+P+FR method where the front bed former pushes the loose soil off the tractor wheels, the majority of the soil for ridge formation remained intact, which resulted in the lowest soil density for this method compared to the other two. Unlike the BF+P+FR method, the P+FR method did not include the front bed former, which caused the soil for ridge formation to be driven over twice. The soil density was, thus, significantly higher than that of the BF+P+FR method and significantly lower than that of the CL method. In the P+FR and BF+P+FR methods, final ridge formation was performed simultaneously with potato planting. The dearth of research in the field of planting and ridge formation hinders the comparison of our results with others. However, our results were comparable with the findings of Sommer



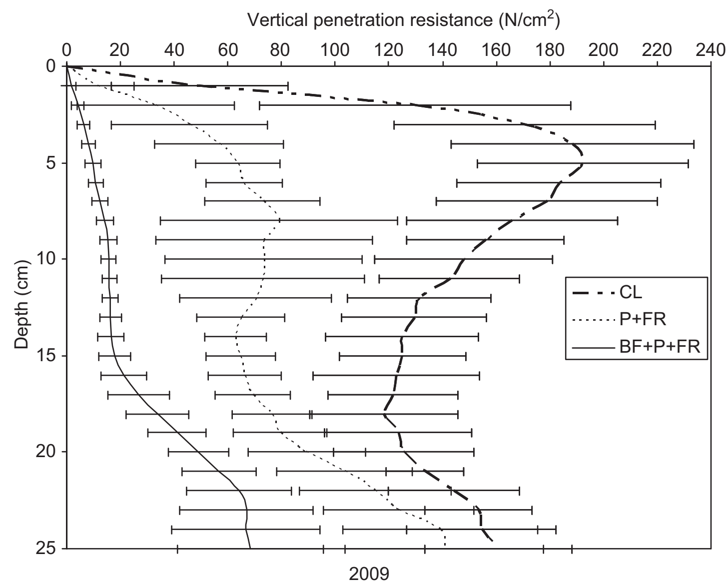


Figure 6. Vertical penetration resistance at depths between 0 and 25 cm according to three different planting and ridge formation methods during 2008 and 2009.
** Horizontal bars represent standard deviation of the mean.*

et al. (1976), which showed an increase in soil density with a higher frequency of tractor passes through the same track of land. Moreover, Mrhar (1995) stated that the soil density on a lightly compacted soil does not exceed 1.40 g/cm^3. In our trial, this soil density was achieved only by the BF+P+FR method. In the other two methods, it ranged between 1.52 and 1.68 g/cm^3. According to Mrhar (1995), such soil would qualify as medium-compacted soil.

Porosity

The porosity of soil for ridge formation is directly linked to soil density (Sommer 1974). In 2008 and 2009, there were statistically significant differences in porosity among the three planting and ridge formation methods. The BF+P+FR method resulted in significantly higher soil porosity compared to the other two methods, while the CL method had significantly lower soil porosity compared to the other two methods (Table 3). In the P+FR method, the soil porosity was, in both years, significantly higher than in the CL method and significantly lower than in the BF+P+FR method. According to Sommer and Zach (1986), 40 to 50% porosity can be found in field soils. In our trial, such porosity was achieved in the BF+P+FR and P+FR methods. On strongly compacted soil, the porosity did not exceed 40% (Sommer and Zach 1986). This result was coincident with the CL method, with a quadruple tractor pass through the same track of land. Likewise, Sommer *et al.* (1976) stated that the porosity of the soil that had been driven over twice decreased by 2 to 3%. In our trial, the reduction was higher. It reached 5–12%.

Soil water content

In 2008, there were statistically significant differences in the water content of the soil for ridge formation among the three planting and ridge formation methods (Table 3). The soil water content in the P+FR method was significantly higher compared to the other two treatments while soil water content in the CL method was significantly lower compared to the other two treatments. It is assumed that in the CL method, this low water content was due to the action of ridging one month after planting, which coincided with a low precipitation period resulting in drier soil. In the BF+P+FR method, soil water content was significantly higher than in the CL method and significantly lower than in the P+FR method ($P<0.05$). In 2009, no statistically significant differences were found in the soil water content among the three planting and ridge formation methods. In 2009, there was a period of strong precipitation immediately before potato emergence, which resulted in a suboptimal implementation of cultivation and ridge formation based on the CL method because the soil was too moist to perform optimal ridge formation.

Mean weight diameter and percentage of soil particles smaller than 10 mm

Soil intended for ridge formation must be loosened. It should contain the highest possible percentage of small soil particles (<2.5 mm) and the smallest possible percentage of large soil particles (>25 mm) (Kouwenhoven and Terpstra 1992). Hence, the MWD and the percentage of soil particles smaller than 10 mm were calculated in the soil intended for ridge formation behind the tractor wheels (Table 3). In 2008 and 2009, statistically significant differences ($P<0.05$) occurred in the MWD among the three planting and ridge formation methods. The BF+P+FR method had a significantly lower MWD compared to the other two treatments while the CL method had significantly higher MWD compared to the other two methods. The MWD in the P+FR method was significantly higher than that of the CL method and significantly lower than that of the BF+P+FR method. Kouwenhoven (1978) stated that, on well-structured soil, the MWD should reach approximately 6 mm because this would enhance the transport of water and heat as well as enable speedy potato emergence. In our trial, this optimal value was almost reached only in the BF+P+FR method. In the CL method, the soil for ridge formation was very compact due to the four tractor passes through the same track of land. Moreover, these passes caused the formation of bigger soil particles and clods in the ridges later in the period of growth, which was extremely unfavourable for potato growth.

In 2008 and 2009, there were statistically significant differences in the percentage of soil particles smaller than 10 mm among the three planting and ridge formation methods. The CL method resulted in a significantly lower percentage of soil particles smaller than 10 mm compared to the other two methods (Table 3). Our results are only partially comparable with those of Heiss (2009), who stated that a cultivator cannot crush the already existing clods on the ridge which was formed during planting. The highest percentage of soil particles smaller than 10 mm occurred in the BF+P+FR method. These values were due to the bed former attached to the front side of the tractor that pushed the loose soil off the wheels. In the P+FR method the percentage of soil particles smaller than 10 mm was significantly higher than in the CL method and significantly lower than in the BF+P+FR method. Few similar studies have been performed abroad. Kouwenhoven *et al.* (2003) determined that, at harvest, the percentage of green tubers was higher if the MWD did not exceed 8 mm.

Cross-sectional area of cultivated soil in the ridge

In both trial years, the CL method resulted in a significantly smaller cross-sectional area of cultivated soil in the ridge in comparison with that of the P+FR and BF+P+FR methods (Table 4). In the CL method, the tines on the PTO-driven cultivator cultivate only one half of the inter-row space, while the majority of the ridge formed during planting remains uncultivated. Similar results were obtained by Heiss (2009), who stated that a cultivator predominantly cultivates the tyre tracks of tractor, planter and cultivator. In both trial years, no statistically significant differences were found between the P+FR and BF+P+FR methods. In these two methods, the final ridges were formed during planting, with the soil subject to

Table 4. Effect of planting and ridge formation methods on the cross-sectional area of cultivated soil in the ridge (CSA), the net cross-sectional area of cultivated soil in the ridge (NCSA) and the distance of the seed tuber from the ridge centre (D) in the years 2008 and 2009 (LSD Test α=0.05). Values are presented as means±s.e.

Planting and ridge formation method	CSA (cm^2)		NCSA (cm^2)		D (cm)	
	2008	2009	2008	2009	2008	2009
CL	575±59^a	489±25^a	288±24^a	331±47^a	5.2±0.5^a	5.1±0.3^a
P+FR	1004±48^b	1001±22^b	648±29^b	676±27^b	1.3±0.3^b	1.5±0.5^b
BF+P+FR	957±45^b	1017±31^b	654±32^b	650±38^b	1.6±0.3^b	0.9±0.4^b

^{ab} Means within a column without a common superscript are significantly different (P<0.05).
CL=classic method.
P+FR=planting and final ridge formation method.
BF+P+FR=bed formation, planting and final ridge formation method.

quality cultivation a day earlier with a rotary harrow. Thus, the whole area of the ridge was formed with loose soil. In these two methods, the cross-sectional area of cultivated soil reached 957–1017 cm^2. This result is in agreement with the findings of Gerighausen (1994), who stated that, at the IRW of 75 cm, the cross-sectional area should exceed 900 cm^2. Kouwenhoven *et al.* (2003) stated that large ridges of this type are suitable for cultivars with larger horizontal tuber span.

Net cross-sectional area of cultivated soil in the ridge

The results for the net cross-sectional area of cultivated soil in the ridge were similar to the results for the cross-sectional area of the ridge. The cross-sectional area in the CL method was, in both trial years, significantly smaller than that of the P+FR and BF+P+FR methods. Hence, the effect of the cultivator was extremely small (Table 4). The cultivator only scattered a small amount of soil above the seed tuber level. In 2008 and 2009, no statistically significant differences were found in the net cross-sectional area of the ridge between the P+FR and BF+P+FR methods. In these methods, the cross-sectional area was considerably larger because the ridge was formed with a soil that was thoroughly loosened up by a rotary harrow shortly before. Heiss (2009) found similar results; after cultivation based on the CL method, the ridge height increased only by 3 to 4 cm, while the majority of the ridge remained uncultivated.

Distance of the seed tuber from the ridge centre

In comparison with the P+FR and BF+P+FR methods, the distance of the seed tuber from the ridge centre in the CL method was significantly higher in both trial years (Table 4). In this method, the cultivation of the inter-row space and final ridge formation occurred one month after planting and after the formation of small ridges (immediately before potato emergence). If during cultivation and final ridge formation the tractor does not drive precisely in the centre of the inter-row space, the seed tuber will not be placed in the exact centre of a newly formed ridge. In both trial years, no statistically significant differences were found in the distance of the seed tuber from the ridge centre between the P+FR and BF+P+FR methods. These two methods involved simultaneous planting and final ridge formation, where the planter precedes the ridger, resulting in the minimum distance of the seed tuber from the ridge centre. Our results agree with the findings of Heiss (2009), who stated that, particularly after cultivation on an inclined terrain, the seed tubers are not placed in a ridge centre.

Green tubers

In both trial years, the CL method gave a significantly higher yield and percentage of green tubers >40 mm in comparison with the P+FR and BF+P+FR methods (Table 5). In both trial years, no statistically significant difference was found in the yield and percentage of green tubers >40 mm between the P+FR and BF+P+FR methods. The percentage of green tubers in the CL method reached 4.1 and 6.2%. In contrast, in the other two methods, it did not exceed 0.5%. It is presumed that such results were reached in the CL method due to a larger distance of the seed tuber from the ridge centre and a smaller net cross-sectional area of cultivated soil in the ridge. Our results are comparable with the findings of Heiss (2009), who stated that the use of a combined machine for soil preparation, planting and final ridge formation reduced the percentage of green tubers to approximately 3% in

Table 5. Effect of planting and ridge formation methods on the yield of green tubers >40 mm (YG), the percentage of green tubers >40 mm (PG), the marketable (MY) and non-marketable tuber yields (NMY) and the percentage of marketable (PM) and non-marketable tuber yields (PNM) (LSD Test α=0.05). Values are presented as means±s.e.

Year	Planting and ridge formation method	YG (kg/ha)	PG (%)	MY (kg/ha)	NMY (kg/ha)	PM (%)	PNM (%)
2008	CL	2001 ± 179^{a}	4.1 ± 0.6^{a}	40247 ± 5955^{a}	9081 ± 392^{a}	81.6 ± 0.6^{a}	18.4 ± 0.6^{a}
	P+FR	218 ± 111^{b}	0.4 ± 0.3^{b}	47230 ± 996^{a}	9362 ± 1854^{a}	83.5 ± 1.1^{b}	16.5 ± 0.5^{b}
	BF+P+FR	124 ± 66^{b}	0.2 ± 0.1^{b}	43601 ± 2461^{a}	6824 ± 1330^{a}	86.5 ± 1.7^{c}	13.5 ± 1.4^{c}
2009	CL	3788 ± 371^{a}	6.2 ± 0.6^{a}	52255 ± 1947^{a}	8754 ± 301^{a}	85.7 ± 0.6^{a}	14.3 ± 0.6^{a}
	P+FR	113 ± 73^{b}	0.2 ± 0.2^{b}	64640 ± 6045^{b}	6595 ± 573^{b}	90.7 ± 1.4^{b}	9.3 ± 1.4^{b}
	BF+P+FR	278 ± 98^{b}	0.4 ± 0.2^{b}	61449 ± 1674^{b}	6501 ± 601^{b}	90.4 ± 1.0^{b}	9.6 ± 1.0^{b}

[abc] Means within a column for a given year without a common superscript are significantly different (P<0.05).
CL=classic method.
P+FR=planting and final ridge formation method.
BF+P +FR=bed formation, planting and final ridge formation method.

comparison with the other methods with separate processes of planting and final ridge formation one month after planting (where it ranged from 5 to 8%). The same author stated that cultivation with a PTO-driven cultivator resulted in the occurrence of cracks in the ridges, which caused greening of the tubers. Struik and Wiersema (1999) and Kouwenhoven *et al.* (2003) found that the percentage of green tubers decreases with an increase of the IRW.

The percentage of green tubers >40 mm depended on the distance of the seed tuber from the ridge centre (Figure 7) with 80.9% of the variability in the percentage of green tubers >40 mm explained by the distance of the seed tuber from the ridge centre. If the seed tuber is located 1 cm from the ridge centre, 0.16% of green tubers >40 mm will occur. If there is a distance of 5 cm between the seed tuber and the ridge centre, the percentage of green tubers >40 mm will reach 5%. The

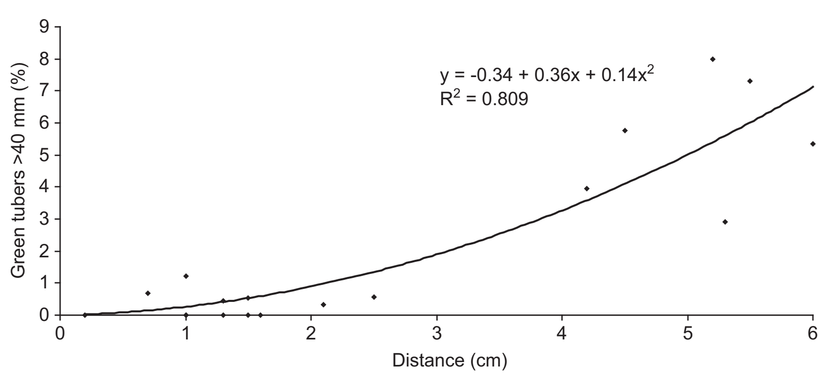


Figure 7. The relationship between the percentage of green tubers >40 mm (y) and the distance of the seed tuber from the ridge centre (x).

literature does not offer a comparable model for the analysis of the distance of the seed tuber from the ridge centre.

Marketable and non-marketable yields

The marketable yield consists of tubers >40 mm. In 2008, no statistical differences were found between the marketable yields for the three different methods (Table 5). In that year, the marketable yields were lower than in 2009. We presume that this outcome occurred due to the planting taking place slightly later in 2008, which, subsequently, shortened the period of growth. In 2009, the CL method had a significantly lower marketable yield than the P+FR and BF+P+FR methods. This result was closely linked with the high percentage of green tubers >40 mm in the CL method. In 2009, no statistically significant difference was found in the marketable tuber yield between the P+FR and BF+P+FR methods. Our results do not agree with the findings of Wulf, Grocholl and Seidel (2001), who stated that there was a slight yield reduction during the simultaneous processes of planting and final ridge formation in comparison with the classic ridging method approximately 2 weeks after planting. Differences between studies might reside in the fact that the trial performed by the above-mentioned authors was performed on heavy soil, while our trial was based on light soil.

The non-marketable yield consists of tubers <40 mm and green tubers of any size. In 2008, no statistical difference was found between methods for the non-marketable yields of tubers (Table 5). In 2009, the non-marketable yield for the CL method was significantly higher than that of the other two methods. As with the marketable yield, this was closely linked with a high percentage of green tubers occurring in the CL method. In 2009, no statistically significant differences were found in non-marketable tuber yield between the P+FR and BF+P+FR methods.

Percentage of marketable and non-marketable tubers

In both trial years, the P+FR method and the BF+P+FR method had a significantly higher percentage of marketable tubers in comparison with the CL method (Table 5). This result occurred primarily because of a lower percentage of green tubers in the P+FR and BF+P+FR methods. In 2008, the BF+P+FR method had a significantly higher percentage of marketable tubers in comparison with the P+FR method, while, in 2009, no statistically significant difference was found between the two methods. In contrast, the CL method resulted in a significantly higher percentage of non-marketable tubers in both trial years, which was mostly due to a higher percentage of green tubers. In 2008, the BF+P+FR method had a significantly lower percentage of green tubers than the P+FR method, while in 2009, no statistically significant differences were found between these two methods.

Theoretical time efficiency

The theoretical time efficiency during planting was similar for the three methods (2.38 h/ha). However, differences occurred in the processes of cultivation and ridge formation, because, in the P+FR and BF+P+FR methods, final ridge formation was performed simultaneously with planting. In the CL method, cultivation and ridging were performed with 1.96 h/ha time efficiency. When comparing all the processes (planting+cultivation+final ridge formation), the CL method required time efficiency of 4.34 h/ha, while the P+FR and BF+P+FR methods needed only 2.38 h/ha of time efficiency. Hence, in comparison with the CL method, these two methods required as much as 45.2% less time for planting and final ridge formation.

When calculating the theoretical time efficiency for the three planting and ridge formation methods, we limited our analysis to the processes of planting and ridge formation. If soil cultivation with a rotary harrow had been considered, the results would have been slightly different. The three methods required a single pass of a rotary harrow before planting. While the P+FR and BF+P+FR methods required deeper soil cultivation (at the depth of approximately 20 cm); the cultivation depth in the CL method was 5 cm lower (approximately 15 cm). Due to the lower depth, the work speed in soil cultivation with a rotary harrow in the CL method would be 10% higher than in the P+FR and BF+P+FR methods. Hence, as a whole, the P+FR and BF+P+FR methods would require approximately 35% less time for soil preparation, planting and final ridge formation when compared to the CL method. To confirm these results, it would be necessary to perform additional measurements within the field trial. Our results are comparable with those of Schmid (2009), who found that, in comparison with the CL method, the efficiency was greater when the combined machine was used for simultaneous soil preparation, planting and final ridge formation.

Conclusion

Overall, the most appropriate method was the BF+P+FR method. This outcome was primarily due to the special bed former attached to the front part of the tractor, which pushed loose soil off the tractor wheels and retained the natural soil structure, improved the soil density, soil porosity and vertical penetration resistance of the soil intended for ridge formation. Moreover, the cross-sectional area of loose cultivated soil in the ridge was sufficiently large, as was the net cross-sectional area of the ridge above the seed tuber. Since final ridge formation was simultaneously performed with planting, the seed tuber was placed in the ridge centre, which subsequently led to a lower yield and percentage of green tubers and a higher percentage of marketable tubers. Compared to the BF+P+FR method, the P+FR method resulted in inferior physical and mechanical properties of the soil, which was due to the two tractor passes through the soil with which ridges were then formed. The CL method was the least suitable. Four tractor passes through the same track of land caused the soil for ridge formation to become compacted with poor physical and mechanical properties. Furthermore, the effect of the cultivator on the cross-sectional area of the ridge was relatively small because it did not scatter a sufficient quantity of loose cultivated soil onto the ridge formed during planting. The cultivator cultivated only half of the inter-row space, causing the major part of the existing ridge to remain uncultivated. A larger distance between the seed tuber and the ridge centre, which was the result of the postponed final ridge formation, caused the occurrence of the highest yield and percentage of green tubers. In addition, this method resulted in the lowest percentage of marketable tubers and the highest percentage of non-marketable tubers. Additionally, one of the downsides of the CL method is that it required as much as 45.2% more time for final ridge formation than the P+FR and BF+P+FR methods. To confirm these results, the trial should be continued in subsequent years on soils with several textures, including different potato cultivars and weather conditions.

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