# Crop Yield and Plant Density under Different Tillage Systems

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## Summary

To determine the optimal ploughing depth and to make tillage simpler and less costly, but also taking account of edaphic and climatic conditions as well as biological and agrotechnical requirements of crops grown, long-term investigations (1994-2009) have been carried out on Stagnic Luvisol of sloping terrains in central Croatia near Daruvar. The paper presents the results relating to plant density and yields of maize (*Zea mays* L.), soybean (*Glycine max* L.), oilseed rape (*Brassica napus* L.), winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.). Investigation results point to the conclusion that high density crops (winter wheat, spring barley and oilseed rape) are suitable for growing under reduced tillage systems. Yields of low density spring crops (maize and soybean) obtained under the no-tillage system are not satisfactory, especially in climatically extreme years.

## Key words

soil tillage, plant density, crops, yield

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## Introduction

Intensive production of field crops practiced until recently to achieve high yields required intensive tillage and application of other high-technology inputs. This concept, however, implies a number of problems, among which relations between product quality and quantity are in the foreground, along with increasingly important ecological sustainability in crop production. Above all, farmers approach production in terms of the cost effectiveness of the applied system.

The traditional, conventional soil tillage, with all its advantages for crops grown, has also some adverse sides, mainly in the domain of the physical, chemical and biological complex of soil fertility, which intensify soil degradation (Bašić et al., 2004) and environmental pollution (Kisić et al., 2005). Possible solutions to these problems lie in the domain of soil tillage, that is, in the concept of more or less reduced tillage, which encompasses the so-called conservation, minimal, rational or no-till systems (Baker et al., 2006). These systems can be defined as tilling practices with the number of treatments reduced by a certain percent (Birkas et al., 2008). Different concepts of reduced tillage have appeared in order to solve problems of soil erosion induced by water and wind, storage of water in arid regions, to prevent underground water pollution and to reduce climate stress impacts (Birkas et al., 2009), as well as to reduce energy consumption, primarily of crude oil and its derivates (Derpsch, 2001).

Current area under reduced tillage is not negligible. There are ca 95 million hectares under no-tillage system in the world; 35 % are in the USA, 22% in Brazil, 15 % in Argentina, and 14 % in Australia. Regarding the application of no-tillage technology, 96 % of areas are in the two Americas, while only 4 % are in the rest of the world (Derpsch, 2001). In European countries, reduced tillage has not been accepted to the extent that could be realistically expected in view of their agroecological conditions (Blanco and Lal, 2008). This is partly due to the economic ability of particular countries to adopt new scientific findings and new technological achievements, and partly to different approaches to the concept of soil tillage as well as to encumbrance of tradition.

## Material and methods

The field experiment was set up near Daruvar (N 45°33·937′, E 17°02·056′) in central Croatia on Stagnic Luvisol (FAO, 2006; IUSS 2006). Mechanical operations, tillage direction (with respect to slope), and the row orientation or planting direction for the five treatments were:

**Ploughing up and down the slope at a depth of 30 cm (PUDS).** Seedbed preparation with a harrow and sowing were performed in the same direction.

**No-tillage (NT)** sowing with a special seeder into the dead mulch up and down the slope. Two to three weeks before sowing weeds were suppressed using total herbicides. In this tillage treatment from no cultivation has been done the beginning of the investigation (1994). Plant residue of the investigated crops was retained on the soil surface.

**Ploughing across the slope at a depth of 30 cm (PAS).**

**Very deep ploughing across the slope at a depth of 60 cm (VDPAS).** In contrast to all other ploughing that was done with multi-furrow ploughs, a single-bottom plough was used in this method.

**Subsoiling at a depth of 60 cm (SSPAS),** subsoiling tines spaced 60 cm apart**,** with ploughing across the slope at a depth of 30 cm.

In the last three tillage methods seedbed preparation and sowing were performed across the slope. Very deep ploughing and subsoiling were not applied every year, since their residual effect was taken into account. These practices were repeated every three to four years in summer, in accordance with the crop rotation of investigated crops. Starting from the set research objective, namely determining the optimal tillage system, we will discuss how tillage, depending on the climatic situation, affected the yields of test crops. Crops grown on each experimental plot followed a typical rotation: maize (1995, 2000 and 2008), soybean (1996, 2001, 2005 and 2009), winter wheat (1996/97, 2001/02 and 2005/06), oilseed rape (1997/98, 2002/03 and 2006/07), and double crop – spring barley with soybean (1999 and 2004).

The results were analyzed using ANOVA (SAS Institute 9.1.3). Significance level of 5 % was applied for all statistical tests. Soil physical and chemical characteristics were measured in four replicates and the data are reported as mean values plus/minus standard deviation.

## Results and discussion

### Major characteristics of the studied soil

Stagnic Luvisol is a soil type with unfavourable physical (unstable structure, unfavourable ratio of texture classes – preponderance of silt particles) as well as unfavourable chemical (low organic matter content, unfavourable soil reaction) characteristics. Table 1 presents the average values of the major physical and chemical characteristics of the studied soil.

### Climate conditions – multiyear average and the studied period

The multiyear average of the mean annual temperature was 10.7 °C (Table 2), while precipitation in the region was 889 mm (Table 3). Eight years of the studied period (1995-2009) had higher precipitation compared to the multiyear average, while lower precipitation was recorded in six years. As regards average temperatures, as many as ten years were warmer compared to the average, one year was at the level of multiyear average, while only four years were colder than the multiyear average. Deviations of monthly precipitation (Graph 1) and temperatures (Graph 2) from the multiyear average are even more interesting. Lower temperatures were on average recorded in all months of the studied period, except in September. Amazing data was obtained when monthly and annual precipitation deficits over the 15 studied years were summed up. Total precipitation deficit in the 15 investigation years, compared to the multiyear average (1960-1999) amounts to incredible 1250 mm, which is almost equal to the average amount of precipitation that falls in 18 months. At the same time, average temperature increased by 0.3 °C. Compared to the average, January, February, April, May, June, July, August, October and November were warmer, while only March, September and December were colder. Recorded data regarding water decrease and temperature increase during

**Table 1.** Physical and chemical characteristics of Stagnic Luvisols evaluated in the experimental plot

| Soil horizon | Horizon depth, cm | Particle size distribution (g $kg^{-1}$)[a] Coarse sand (2-0.2 µm) | Fine sand (0.2-0.02µm) | Silt (0.02-0.002µm) | Clay (< 0.002µm) | Texture class |
|---|---|---|---|---|---|---|
| Ap + Eg[b] | 0 – 24 | 18[c] ± 4.7 | 586 ± 37 | 242 ± 35 | 154 ± 25 | Sandy loam |
| Eg + Btg | 24 – 35 | 21 ± 5.5 | 571 ± 59 | 260 ± 54 | 148 ± 44 | Sandy loam |
| Btg | 35 – 95 | 5 ± 2.3 | 545 ± 69 | 254 ± 32 | 196 ± 40 | Sandy loam |
| Average value of soil bulk density ($\rho_b$)[d] after 15 years of investigation, Mg $m^{-3}$ | | | | | | |
| PUDS | | NT | PAS | VDPAS | | SSPAS |
| 1.58 ± 0.10 | | 1.60 ± 0.15 | 1.60 ± 0.10 | 1.57 ± 0.13 | | 1.59 ± 0.10 |
| | | pH in KCl | Soil organic matter (g $kg^{-1}$) | Available P (kg $ha^{-1}$) | Available K (kg $ha^{-1}$) | |
| Ap + Eg | 0 – 24 | 4.21[c] ± 0.15 | 16 ± 3.3 | 172 ± 18 | 308 ± 6 | |
| Eg + Btg | 24 – 35 | 4.20 ± 0.18 | 14 ± 4.2 | 65 ± 4 | 123 ± 8 | |
| Btg | 35 – 95 | 4.81 ± 0.23 | 6 ± 3.8 | 244 ± 24 | 502 ± 12 | |

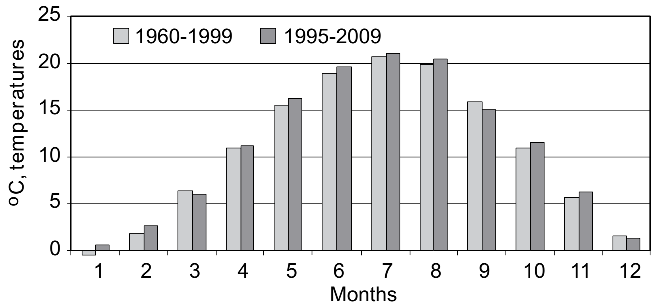
[a] Average of all treatments; [b] according to FAO (1990); [c] data expressed as an average of four replications ± standard deviation; [d] average of 20 measurements

**Table 2.** Monthly and annual deviations of mean monthly temperatures (ºC) in the studied period (1995-2009) compared to the multiyear average (1960-1999)

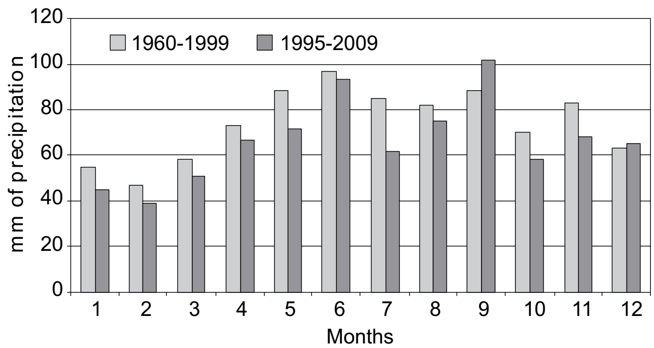
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average, 1960-99 | -0.4 | 1.9 | 6.3 | 10.9 | 15.5 | 18.9 | 20.6 | 19.9 | 15.9 | 10.9 | 5.7 | 1.6 | 10.7 |
| 1995 | 1.5 | 4.7 | -0.9 | 0.7 | -0.3 | -0.7 | 2.7 | -0.5 | -1.1 | 0.7 | -1.4 | 0.1 | 0.4 |
| 1996 | -0.9 | -3 | -3.1 | -0.1 | 1.7 | 1.3 | -1.2 | -0.1 | -3.1 | 0.3 | 2.1 | -2.8 | -0.8 |
| 1997 | -1.1 | -1.3 | -3.2 | -2.5 | -0.4 | -2.8 | -2.7 | 0 | 0 | 0 | 0 | 0 | -1.2 |
| 1998 | 3.5 | 2.7 | -2 | 1.3 | -0.4 | 1.3 | 0.5 | 0.4 | -0.6 | 1 | -2.3 | -4.5 | 0 |
| 1999 | 1.5 | -0.7 | 1.7 | 0.8 | 0.7 | 0.4 | 0.4 | 0.4 | 2.1 | 0.1 | -2 | 0.6 | 0.4 |
| 2000 | -1.4 | 2.4 | 0.5 | 2.7 | 1.2 | 1.8 | -0.2 | 1.9 | -0.5 | 2.3 | 4.3 | 3.1 | 1.5 |
| 2001 | 4 | 2.1 | 3.7 | -0.8 | 1.9 | -1.4 | 0.6 | 1.6 | -1.9 | 2.9 | -2.4 | -4.6 | 0.4 |
| 2002 | 0.8 | 4 | 1.7 | -0.5 | 2.2 | 1.8 | 1.1 | 0.2 | -1.2 | 0.4 | 4.3 | 0.4 | 1.2 |
| 2003 | -0.6 | -3.9 | -0.4 | -0.5 | 3 | 4.7 | 1.6 | 3.8 | -0.9 | -1.9 | 2.5 | -0.1 | 0.6 |
| 2004 | -0.3 | 0.3 | -1.2 | 0.4 | -1.3 | -0.2 | -0.2 | 0.3 | -1 | 2.4 | 0.4 | 0.2 | -0.1 |
| 2005 | 0 | -4.3 | -2.1 | -0.2 | 0.4 | 0 | 0.2 | -1.4 | 0.2 | -0.3 | -0.6 | -0.1 | -0.7 |
| 2006 | -1.5 | -0.7 | -1.2 | 0.7 | -0.3 | 0.2 | 1.9 | -1.3 | 0.7 | 1.5 | 2.4 | 2.3 | 0.3 |
| 2007 | 6.6 | 4.7 | 1.5 | 1.5 | 2 | 2.6 | 1.9 | 1.2 | -2.2 | -1.6 | -1.4 | -1.5 | 1.2 |
| 2008 | 2.6 | 2.5 | 0.7 | 0.8 | 1.2 | 1.8 | 0.4 | 0.6 | -1.6 | 1.5 | 1.2 | 2.1 | 1.1 |
| 2009 | -1.0 | 0.7 | 0.5 | 2.8 | 2 | 0.1 | 1.1 | 1.8 | 1.8 | 0.1 | 2.8 | 2.2 | 1.2 |
| Average,1995-09 | 0.5 | 2.6 | 6.0 | 11.4 | 16.4 | 19.6 | 21.1 | 20.5 | 15.3 | 11.5 | 6.4 | 1.4 | 11.1 |

**Table 3.** Monthly and annual deviations of total precipitation (mm) in the studied period (1995-2009) compared to the multiyear average (1960-1999)

| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average, 1960-99 | 55 | 47 | 58 | 73 | 88 | 97 | 85 | 82 | 88 | 70 | 83 | 63 | 889 |
| 1995 | -9 | 21 | -16 | -34 | -8 | 57 | -82 | 54 | 95 | -57 | 6 | -4 | 23 |
| 1996 | 20 | -23 | -34 | -8 | 6 | -57 | 8 | -45 | 138 | -25 | 26 | -3 | 4 |
| 1997 | -8 | 8 | -35 | -30 | -22 | -6 | 27 | -3 | -66 | -6 | 23 | 1 | -118 |
| 1998 | 7 | -42 | 6 | -4 | -13 | 3 | -3 | 2 | 26 | 49 | -6 | -16 | 9 |
| 1999 | -7 | 5 | -35 | 36 | 21 | 55 | -30 | 2 | -15 | -25 | -15 | 12 | 4 |
| 2000 | -44 | -22 | -4 | 21 | -41 | -60 | -34 | -38 | -25 | -21 | 6 | 2 | -260 |
| 2001 | 37 | -26 | 39 | -29 | -60 | 97 | -23 | -70 | 92 | -58 | 21 | -6 | 14 |
| 2002 | -15 | 11 | -21 | 50 | 68 | -49 | -4 | -17 | 23 | -15 | 22 | -34 | 19 |
| 2003 | -53 | -41 | -37 | -33 | -66 | -58 | -38 | -46 | -25 | 39 | -21 | -30 | -412 |
| 2004 | 12 | 14 | -4 | 80 | -42 | 21 | -26 | -24 | 29 | 21 | -16 | 29 | 93 |
| 2005 | -42 | 37 | -8 | -8 | -26 | -59 | 27 | 80 | -5 | -53 | -55 | 61 | -51 |
| 2006 | -22 | -19 | -4 | 15 | 23 | -7 | -74 | 63 | -27 | -44 | -48 | -27 | -171 |
| 2007 | -5 | 15 | 29 | -66 | 35 | -68 | -71 | 0 | 43 | 32 | -10 | 4 | -62 |
| 2008 | -33 | -39 | 34 | -16 | -67 | 66 | 17 | -33 | 7 | -13 | -28 | 15 | -92 |
| 2009 | 16 | -14 | -13 | -62 | -54 | 5 | -44 | -32 | -79 | -8 | 7 | 22 | -258 |
| Average, 1995-09 | 45 | 39 | 51 | 67 | 72 | 93 | 62 | 75 | 102 | 58 | 77 | 65 | 805 |




**Graph 1.** Mean monthly temperatures (°C) in the multiyear average (1960-1999) and in the studied period (1995-2009)




**Graph 2.** Mean monthly precipitation (mm) in the multiyear (1960-1999) and in the studied period (1995-2009)

research period (1995-2009) indicates future difficulties in spring crop growth unless winter water is preserved.

### Plant density of crops grown

Plant density of crops grown showed that in most cases a significantly lower number of plants at harvest in the NT treatment compared to other treatments (Table 4). However, data on plant density obtained in these investigations may lead to wrong conclusions. Although relatively lower plant density was recorded in the NT treatment, sometimes without significant differences, yields achieved in this treatment were often very significantly lower compared to the other treatments. Although the number of plants in the NT treatment was relatively satisfactory (especially in the case of maize and soybean), the achieved grain yields per plant were much lower in the NT treatment compared to the other treatments (Table 5). Height and thickness of maize plants, ear size and kernel number per ear were much lower in the NT treatment compared to the other treatments. The same was observed for soybean stalk height, number of pods per plant and seed number per soybean pod. Unfortunately, these parameters were not followed up, so they can be explained on the basis of visual observations over the 15 investigation years.

The above consideration indicates that the established plant density cannot be a decisive parameter for (un)acceptance of novel tillage methods. But, yield and yield cost per treatment will give much more exact data on the possibility of applying new tillage methods.

### Achieved yields of crops grown

Yields of crops grown are shown in Table 5. Maize was grown in the trial field in the first investigation year (1995) and then again in 2000 and 2008. PUDS was found to be best suited to the conditions of the first year, which was climatically very favourable for the production of low density spring crops. This treatment gave a significantly higher yield compared to other treatments while the significantly lowest maize grain yield was achieved by the NT treatment. Significantly lower yield was again recorded under NT in 2000 when maize was sown again in the trial field, whereas it was significantly higher in all treatments involving across-the-slope tillage compared to PUDS and NT. The only reason for higher yields in treatments involving across-the-slope tillage compared to PUDS and NT were the climatic conditions during the year 2000 (Tables 2 and 3). Drought started in the first decade of May of that year and continued until November. All the months in that period were characterized by expressly negative water balance. Drought had higher impact in PUDS and NT treatments than in treatments involving tillage across the slope. Obviously, across-the-slope tillage enabled better storage of water from the preceding winter period. In 2008 when maize was grown again in the trial field, treatments with tillage and sowing across the slope rendered better results. All treatments in which tillage and sowing were performed across the slope gave higher yields compared to PUDS and NT. It is interesting to note that in the given year the grain yield of maize in the NT treatment was almost two times higher than in the first two years (1995 and 2000) when the same crop was grown in the trial field.

Soybean was another low density spring crop included in these investigations. It was sown as a single crop in 1996, 2001, 2005 and 2009 and in consociation with spring barley in 1999 and 2004. The decisive influence on the soybean seed yield in the first investigation year was that of the climatic conditions. Less than 50 % of long-term average precipitation fell in June of 1996, but at the same time that month's temperature was at the level of the multiyear average for July. For these reasons, soybean lacked sufficient moisture for normal development already at the start of growth, which was specially reflected in the establishment of plant density under NT. Although July precipitation was in the average range, this was not enough to compensate the deficit from June. August, again, had less than 50 % of multiyear precipitation average and thus the drought continued. Accordingly, drought lasted from June to August of that year. Climatic conditions were quite opposite in September. Three times more precipitation fell in September compared to the multiyear average. October, however, had only a fifth of average precipitation. The described climatic conditions indicate that the year 1996 was expressly unfavourable for the production of spring crops. Under such climatic conditions, weed management is very difficult in treatments with reduced tillage, and especially with NT. Low soybean yields were obtained that year in all treatments as a consequence of adverse climatic conditions, notably in the first part of the year (drought) and towards the end of the growing period (extreme rainfall). Regarding yields, PAS and VDPAS treatments gave the best results. Approximately equal soybean yields were achieved with PUDS and SSPAS and the lowest under NT. Lower yield was obtained in the latter

**Table 4.** Plant density of investigated crops according to tillage treatments*

| Tillage treatments | PUDS | NT | PAS | VDPAS | SSPAS |
|---|---|---|---|---|---|
| Maize, 1995 | 60.054$^{a}$ | 51.644$^{a}$ | 58.791$^{a}$ | 60.485$^{a}$ | 60.582$^{a}$ |
| Maize, 2000 | 60.641$^{a}$ | 48.447$^{b}$ | 60.506$^{a}$ | 60.193$^{a}$ | 60.332$^{a}$ |
| Maize, 2008 | 60.366$^{a}$ | 58.414$^{a}$ | 61.056$^{a}$ | 61.490$^{a}$ | 60.843$^{a}$ |
| Soybean, 1996 | 1.028.501$^{ba}$ | 979.951$^{b}$ | 1.092.550$^{a}$ | 1.070.150$^{a}$ | 962.500$^{b}$ |
| Soybean, 1999 | 477.500$^{a}$ | 202.500$^{d}$ | 371.750$^{b}$ | 371.250$^{b}$ | 292.500$^{c}$ |
| Soybean, 2001 | 1.122.500$^{a}$ | 915.000$^{c}$ | 1.037.500$^{b}$ | 1.033.750$^{b}$ | 1.147.500$^{a}$ |
| Soybean, 2004 | 547.500$^{a}$ | 245.000$^{c}$ | 385.000$^{b}$ | 361.250$^{b}$ | 282.500$^{c}$ |
| Soybean, 2005 | 1.150.000$^{ba}$ | 955.000$^{c}$ | 1.167.500$^{a}$ | 1.156.250$^{ba}$ | 1.102.500$^{b}$ |
| Soybean, 2009 | 1.207.500$^{a}$ | 870.000$^{c}$ | 1.187.500$^{ba}$ | 1.195.000$^{ba}$ | 1.140.000$^{b}$ |
| Wheat, 1997 | 577$^{a}$ | 325$^{c}$ | 582$^{a}$ | 547$^{b}$ | 592$^{a}$ |
| Wheat, 2002 | 605$^{a}$ | 454$^{c}$ | 584$^{ba}$ | 577$^{b}$ | 577$^{b}$ |
| Wheat, 2006 | 595$^{a}$ | 564$^{b}$ | 590$^{a}$ | 604$^{a}$ | 599$^{a}$ |
| Oil seed rape, 1998 | 289$^{a}$ | 280$^{b}$ | 288$^{a}$ | 275$^{b}$ | 273$^{b}$ |
| Oil seed rape, 2003 | 273$^{b}$ | 268$^{b}$ | 297$^{a}$ | 260$^{c}$ | 252$^{c}$ |
| Oil seed rape, 2007 | 187$^{a}$ | 181$^{ba}$ | 190$^{a}$ | 170$^{b}$ | 171$^{b}$ |
| Barley, 1999 | 304$^{a}$ | 252$^{d}$ | 274$^{c}$ | 271$^{c}$ | 285$^{b}$ |
| Barley, 2004 | 289$^{a}$ | 252$^{d}$ | 276$^{b}$ | 269$^{c}$ | 285$^{a}$ |

*Plant density in time of harvest crops; Maize and Soybean – plants $ha^{-1}$; wheat, oil seed rape and barley - plants $m^{-2}$

**Table 5.** Grain yield (t $ha^{-1}$) of trial crops according to tillage treatments

| Tillage treatments | PUDS | NT | PAS | VDPAS | SSPAS |
|---|---|---|---|---|---|
| Maize, 1995 | 8.63$^{a}$ | 3.47$^{d}$ | 6.57$^{c}$ | 6.73$^{cb}$ | 7.24$^{b}$ |
| Maize, 2000 | 7.02$^{c}$ | 3.28$^{d}$ | 7.82$^{ba}$ | 7.97$^{a}$ | 7.48$^{b}$ |
| Maize, 2008 | 8.59$^{b}$ | 6.05$^{c}$ | 9.68$^{a}$ | 9.07$^{b}$ | 8.95$^{b}$ |
| Soybean, 1996 | 1.98$^{a}$ | 1.45$^{b}$ | 2.13$^{a}$ | 2.09$^{a}$ | 1.92$^{a}$ |
| Soybean, 1999 | 1.11$^{ba}$ | 0.42$^{c}$ | 1.07$^{ba}$ | 1.22$^{a}$ | 0.88$^{b}$ |
| Soybean, 2001 | 3.05$^{ba}$ | 2.00$^{c}$ | 2.88$^{b}$ | 2.92$^{b}$ | 3.34$^{a}$ |
| Soybean, 2004 | 1.15$^{a}$ | 0.51$^{b}$ | 1.13$^{a}$ | 1.18$^{a}$ | 0.89$^{a}$ |
| Soybean, 2005 | 3.34$^{ba}$ | 2.12$^{c}$ | 3.41$^{ba}$ | 3.59$^{a}$ | 3.13$^{b}$ |
| Soybean, 2009 | 3.77$^{a}$ | 2.26$^{b}$ | 3.54$^{a}$ | 3.62$^{a}$ | 3.15$^{a}$ |
| Wheat, 1997 | 4.41$^{cb}$ | 2.97$^{d}$ | 4.57$^{b}$ | 4.09$^{c}$ | 5.14$^{a}$ |
| Wheat, 2002 | 5.95$^{a}$ | 4.35$^{c}$ | 5.61$^{ba}$ | 5.55$^{ba}$ | 5.45$^{b}$ |
| Wheat, 2006 | 5.58$^{a}$ | 5.84$^{a}$ | 5.79$^{a}$ | 6.02$^{a}$ | 5.89$^{a}$ |
| Oil seed rape, 1998 | 2.48$^{a}$ | 2.29$^{a}$ | 2.23$^{a}$ | 2.18$^{a}$ | 2.08$^{a}$ |
| Oil seed rape, 2003 | 2.33$^{ba}$ | 2.02$^{bac}$ | 2.44$^{a}$ | 1.94$^{bc}$ | 1.87$^{c}$ |
| Oil seed rape, 2007 | 1.51$^{a}$ | 1.45$^{a}$ | 1.48$^{a}$ | 1.39$^{a}$ | 1.39$^{a}$ |
| Barley, 1999 | 2.34$^{a}$ | 1.46$^{c}$ | 1.87$^{bac}$ | 1.84$^{bc}$ | 2.10$^{ba}$ |
| Barley, 2004 | 2.15$^{a}$ | 1.54$^{b}$ | 1.91$^{ba}$ | 1.87$^{ba}$ | 2.14$^{a}$ |

treatment compared to all the other treatments. When soybean was sown again in the trial field (2001), SSPAS rendered the best results while VDPAS was found to be the best practice in 2005. Somewhat better results of soybean production under reduced tillage practices were achieved in the investigations of Husnjak et al. (2002) and Košutić et al. (2005 and 2006).

In both years (1999 and 2004) when soybean was sown together with spring barley, VDPAS was found to be the best practice. Significantly lower soybean yield was obtained under NT compared to other treatments whereas there were no significant differences between other treatments. Results of these investigations indicate that soybean did not respond favourably to NT treatment. Plant density and soybean yield achieved under NT clearly point to the need of further, more detailed investigation of such sowing.

Winter wheat was grown in the trial field in 1997, 2002 and 2006 (Table 5). Although significantly lower yield of winter wheat was obtained under NT in 1997 and 2002, differences between yields were not significant when winter wheat was sown again in crop rotation (2006). Indeed, the 2006 yield under NT was slightly higher compared to some other treatments (PUDS and PAS). Similar situation was recorded for spring barley (Table 5), which was sown in 1999 and 2004 in consociation with soybean. Significantly lower yield in both years was obtained under NT compared to PUDS and SSPAS.

In these 15-year investigations, oilseed rape was found to be the most successful crop with respect to reduction of the number of tillage practices (Table 5). Yields of oilseed rape achieved under NT in the three investigation years (1997/98, 2002/03 and 2006/07) were in the range of yields obtained in other treatments. For this reason, no significant differences in yields were determined among individual treatments in two years.

These investigations allow the conclusion that high plant density crops: winter wheat, spring barley and oilseed rape are relatively suitable crops for growing under reduced tillage systems. Yields achieved in the production of low density spring crops under NT are not satisfactory, particularly in climatically extreme years. However, it should be emphasized that the increasingly important role in achieved yields was that of the monthly distribution of precipitation rather than its annual amount. High daily precipitation was often recorded during the 15-year investigations, which had a more negative than positive effect on the plant density of crops grown. This daily precipitation sometimes accounted for 70 % of total monthly precipitation. In the droughty years, spring crops deteriorate due to increased soil compaction and higher incidence of pests (rodents) and the problem of higher incidence of diseases occurs in excessively wet years. But, differences were also observed between spring crops. Soybeans tolerated tillage practices in climatically favourable years, but with higher risk of applying reduced tillage systems in dry years. Maize was shown to be a very risky crop with a very bad response to reduction of conventional tillage, even in climatically 'good' years. Maize intolerance to reduction of soil tillage especially in dry years has also been reported by Kisić et al. (2002), Jug et al. (2007) and Kvaternjak et al. (2008).

Efficiency of the studied tillage systems has been evaluated in this paper on the basis of the yields achieved, which is only one of the ways of showing the efficiency and cost effectiveness of tillage systems applied. Košutić et al. (2005) reported that fuel savings in different reduced tillage systems are from 10 to as much as 75 L $ha^{-1}$ of diesel equivalent. Sørensen and Nielsen (2005) report that in the case of reduced tillage the energy input was reduced by 18-53 % compared to conventional tillage, depending on the methods and techniques applied. Direct drilling reduced the energy input by 75-83 % and labour demand and $CO_2$ emissions would be reduced by approximately the same percentage. The same authors report that reduced tillage with NT led to 25-41 % reductions in the cost per hectare compared to traditional methods. When all parameters are taken into consideration, the presented results and experiences allow the conclusion that there are reasonable prospects of applying NT or some other form of reduced tillage in primary plant production.

According to the foregoing consideration, cost effectiveness of particular tillage systems would be somewhat different if their cost effectiveness should include the reduction of tillage cost ensuing from the application of reduced tillage systems. More precisely, production costs in the NT treatment were appreciably more reduced compared to the recorded yield decrease, thereby making NT more cost effective. This especially holds for the production of high density winter and spring crops.

Reduced tillage is not a unilateral and unambiguous concept; it is a conceptually very complex system requiring a complex of approaches to considering all its determinants. Thus, reduced tillage should not be evaluated solely in terms of achieved yields, but also from the ecological, energetic, organizational, economic, social and other aspects. As Philbrook et al. (1991) outline, the crop production under conservation tillage is likely to be further developed, primarily for economic reasons (cheaper production) and also because of ever stricter environmental protection measures.

## Conclusions

These 15-year investigations allow the conclusion that high density crops: winter wheat, spring barley and oilseed rape are relatively suitable crops to be grown under reduced tillage systems. Yields achieved in the production of low density spring crops (maize and soybean) under NT were not satisfactory, especially in climatically extreme years. However, considering lower yields, on the one side, and energy saving for tillage, reduced labour and emission of gases (especially $CO_2$), on the other side, this system should be paid more attention in the future research work.

For these reasons and because of the actuality of applying NT and other reduced tillage methods, diversity of agroecological conditions (soil and climate) in Croatia, particularly in regions with expressive field production (Slavonija, Podravina, Moslavina and Baranja), and recognizing the complexity of the problems involved, that is, application of a new tilling technology, the authors think that further detailed, long-term and complex research work is absolutely necessary. Long-term investigations should provide answers concerning the real potential of NT and other reduced tillage systems in this country – in which soil types, in which climatic conditions, with which variants of simplified tillage, by which technical means, in which time period and at which intervals of application.

What kind of the tillage systems will prevail in crop production will most probably depend on fuel prices, primarily on the prices of crude oil and its derivates, thus pushing into the background all the other aspects of different soil tillage methods.

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