FINAL REPORT

Optimal soil tillage methods for crop production in the Swartland wheat-producing area of the Western Cape (Project P07/9/139)

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ABSTRACT

Soil tillage affects both the profitability and sustainability of cropping systems. Minimum and no-tillage systems are propagated because research has shown that these systems may reduce production costs and improve biological sustainability when compared to conventional systems, in which mouldboard and disc ploughs are used. However, responses to different tillage systems may differ for different crops as well as different soil and climatic conditions. In this long-term study, conducted under a Mediterranean-type climate, minimum and no tillage out-yielded conventional mouldboard-based tillage. Minimum and no-tillage systems can therefore be used successfully to produce spring-type canola, lupin and wheat crops in sustainable crop rotation systems under rain-fed conditions in the Swartland wheat-producing area of the Western Cape province of South Africa. Higher wheat yields when wheat is grown in a crop rotation system compared to a monoculture system can be ascribed to fewer problems with grassy weeds, but also to improved soil organic C and nitrogen contents, which result in more plant-available mineral nitrogen and hence more vigorous crop growth. Grain yields of wheat and canola crops responded positively to increased N application rates and the results suggest that application rates of more than 100 kg ha^{-1} should be considered where no and minimum tillage are practised. Higher nitrogen application rates resulted in higher grain protein and hence improved bread-making quality of the wheat, but the oil content and thus quality of canola tend to decrease with higher N application rates.

PROBLEM DESCRIPTION

Soil tillage affects both the profitability and sustainability of cropping systems. Minimum and no-tillage systems are propagated because research has shown that these systems may reduce production costs and improve biological sustainability when compared to conventional systems, in which mouldboard and disc ploughs are used. However, the optimum method of tillage may differ for different crops because of factors such as rooting systems, sensitivity to soil compaction and soil-borne diseases. Soil and crop responses to different soil tillage systems may only show after a considerable period of time, however, and may differ for different climatic regions and soil types. For these reasons, site-specific long-term results from soil tillage research are often not available. The soil tillage trail at Langgewens Experimental Farm was started in 1976 and, for this reason, could provide unique results regarding the long-term effects of different tillage methods on soil fertility properties and the subsequent growth and yield of crops grown in the Swartland wheat-producing area of the Western Cape.

LITERATURE REVIEW

Crop production is affected by environmental factors such as climate and soil fertility, as well as by the production techniques used. Soil fertility, as measured by soil physical, chemical and biological characteristic, is however also affected by production techniques, such as crop rotation, soil tillage and fertilisation (Sprague & Triplett, 1986).

Hao *et al*. (2000), for example, reported that tillage-induced changes in physical properties, such as bulk density (BD), penetration resistance, soil water content and aggregate stability, are inter-related and depend on soil texture, water content at the time of tillage and the time lags between tillage and physical property measurements.

Tillage systems that leave crop residues on the soil surface will effect soil physical properties and influence soil erosion by water and wind, therefore strengthening the need for reduced tillage and even direct sowing in erosion-stricken areas. However, the presence of defective soils and some meteorological conditions may require conventional plough tillage (Malicki *et al*., 1997).

Soil physical properties can also be affected by crop rotation, but little information is available on the relative effectiveness of the different alternate crops. Chan & Heenan (1996) found that soils that had been used for lupine and canola production were more porous and had lower shear strength than soils that had been used for field pea and barley production. They therefore suggested that conservation tillage practices, namely direct drilling and reduced tillage, may help to preserve the benefits of the different crops.

Soil chemical properties are also affected by method of tillage. Higher levels of soil organic C, total N and extractable P, as well as lower concentrations of NO_3^--N, are directly related to surface accumulation of crop residues in systems of conservation tillage (Campbell *et al*., 2000). The levels of both organic carbon and total nitrogen increased with decreased tillage intensity, but the C/N ratio did not show any affect (Ekeberg & Riley, 1997). The effect also varies with soil depth. Campbell *et al*. (1996) reported that no tillage increased the concentration of organic C and N in the 0 to 75 mm soil depth, but not in the 75 to 150 mm depth, while results obtained under rain-fed Mediterranean conditions showed that no tillage did not increase the organic matter (OM) and extractable mineral N content of the soil after six years, due to the small amounts of crop residues returned to the soil annually (Bellido *et al*., 1997). This is typical for a semi-arid climate, suggesting that a longer period will be needed to observe significant changes in the OM and N content in the soil under such conditions.

Crop rotation usually increases the content of soil organic matter when compared to monoculture, and this is especially true when no tillage is used (Løpez-Fando & Almendros, 1995). Significant increases in the organic matter content were also observed due to the presence of legume crops in rotations in combination with no tillage (Fettel & Gill, 1995; Stringi & Giambalvo, 1999; Campbell *et al*., 2000).

High rates of N fertiliser may also affect soil chemical properties, resulting in a decrease in soil pH with no tillage compared to other tillage systems in sub-humid climates (Salinas-Garcia *et al*., 1997), while the effect of tillage on soil CEC appeared to be dependent on the mechanical mixing of soil by mouldboard ploughing. Ekeberg & Riley (1997) reported that reduced tillage lowered the pH by about 0.1 to 0.3 units when compared to plough tillage in a long-term trial on morainic loam soils in southeast Norway.

Differences in rainfall during the growing season have a marked effect on wheat yield. In dry years under rain-fed conditions in Mediterranean-type climates, the grain yields of wheat were higher when no tillage was used instead of conventional tillage (Løpez-Bellido *et al*., 1996). Similar results were obtained by Pratley (1995), Du-Bing *et al*. (2000) and Maali & Agenbag (2003). Bonari *et al*. (1995) found no significant differences in the yield of rapeseed when conventional tillage and minimum tillage were compared on a sandy soil. They therefore recommended that, on sandy soil, minimum tillage can be used for at least three consecutive years due to time and energy savings as well as cost reductions. However, if used for longer periods of time, it might be necessary to include an occasional conventional tillage treatment to reduce soil compaction.

The favourable effect of crop rotation on yield has long been known (Heenan *et al*., 1994; Løpez-Fando & Almendros, 1995; West *et al*., 1996). However, the effect of previous rotations on wheat productivity changes as a result of seasonal rainfall during the wheat or legume phases (Heenan *et al*., 1998). Although grain yield obtained with wheat did increase with the addition of N fertiliser in systems of wheat monoculture, yields from continuously cropped wheat were usually lower than those after a lupine crop (Heenan *et al*., 1998).

Heenan *et al*. (1994) reported slightly higher grain yields as a result of a higher number of ears, higher harvest index and larger grains, but lower grain protein with the direct drilling of wheat compared to conventional tillage. Tillage methods were also found to affect grain protein content, test weight and some grain quality indices because of the effect on moisture and nitrate-N in the soil (Raath & Agenbag, 1997; Løpez-Bellido *et al*., 1998; Maali & Agenbag, 2006). However, in a study done in Italy, Giambalvo *et al*. (1999) showed that no tillage reduces grain protein content. Crop rotations that included legumes have been found to have beneficial effects on wheat grain quality when compared to continuous wheat by improving the protein content and the rheological properties of the dough (Heenan *et al*., 1994, 1998; Løpez-Bellido *et al*., 1998; Giambalvo *et al*., 1999; Galantini *et al*., 2000; Maali & Agenbag, 2006). This effect can be ascribed to the biological fixed residual N in the soil profile, which increases N supply to and uptake by the wheat crop. Ramsey & Callinan (1994) found that the highest canola seed protein was always obtained with the highest application of N, but that the percentage of oil in the seed generally decreased with increasing N fertiliser applications.

From the above literature it is clear that soil characteristics and the resultant growth and yield of crops are affected by the method of soil tillage and the crop rotation used, but that responses may differ for different climatic regions and soil types. Some responses may only become clear after several years of tillage. For these reasons, the results of long-term tillage trails in the Swartland wheat-producing area of the Republic of South Africa will be important to verify results obtained in other climatic regions and soil types.

MATERIAL AND METHODS

The original experiment started in 1976, but this report will only focus on with the period from 2001 to 2010 (period of present treatments). The experiment was conducted at Langgewens Experimental Farm (33º 175, 18º 42E) on a shallow (250 to 300 mm) sandy loam soil with a gravel and stone (shale) content of 44.6% in the A horizon. Rainfall at this locality showed a typical Mediterranean-type distribution, with a long-term average of 334 mm per annum, of which about 80% occurs during the autumn/winter/spring months of April to September.

The following treatments were applied:

i) Crop rotations (since 1990)

WW - Wheat continuously (monoculture)

WLWC - Wheat /lupins/wheat/canola rotation

ii) Soil-tillage methods (applied since)

Conventional tillage (Conv till): Chisel plough (150 mm) after the first autumn rains, followed by a mouldboard plough (200 mm) and fieldspan at planting time (1976).

Tine tillage (Tine till): Chisel plough (150 mm) after the first autumn rains, followed by a fieldspan at planting time (1976).

Minimum tillage (Min till): Chisel plough (75 to 100 mm) after the first autumn rains, followed by pre-plant non-selective chemical weed control at planting time (1982)

No tillage (No till): Pre-plant non-selective chemical weed control at planting time (1976).

Minimum tillage every second year with no till in between (1996)

Minimum tillage every third year with no till in between (1996)

Minimum tillage every forth year with no till in between (1996)

All plots were planted with a no till planter fitted with knife-openers and presswheels (2000, previously no-tillage planter with disc openers)

iii) N application rates (since 2001*)

20 N ha^{-1} band placed at planting (20 N ha^{-1})
20 N ha^{-1} band placed at planting + 40 N ha^{-1} (30 days after planting) (60 N ha^{-1})
20 N ha^{-1} band placed at planting + 40 N ha^{-1} (30 days after planting) + 40 N ha^{-1} (60 days after planting) (100 N ha^{-1})

- Rates of 60, 100 and 140 N ha^{-1} were applied during the period 1990 to 2000

All treatments were replicated four times with plot sizes of 5 m x 16 m.

Similar agronomical practices with regard to planting densities, post-emergence weed control, insect and disease control were applied to all tillage treatments.

Data for soil properties, crop development, yield and quality were collected, but not all the parameters were measured every year because lupins and canola were planted once in a four-year cycle only. Although this project was only funded for the period 2008 to 2010, data on crop yields for the period 2001 to 2010 will be presented.

RESULTS

Soil properties

Soil samples were taken at depths of 0 to 15, 15 to 30 and 30 to 45 cm before planting in 2008, to determine the soil pH, organic carbon content, total nitrogen content as well as macro-elements (Table 1) and micronutrients (Table 2), using standard procedures (The Non-affiliated Soil Analysis Work Committee, 1990) .

Table 1. Effect of soil tillage and crop rotation on soil chemical properties at Langgewens (2008)

	Depth cm	**pH $_{KCl}$**	**K mg kg^{-1}**	**P mg kg^{-1}**	**C %**	**N %**	**Ca cmol kg^{-1}**	**Mg cmol kg^{-1}**	**S mg kg^{-1}**
Wheat monoculture									
Conv till	0-15	4.4	106	62	0.43	0.06	1.91	0.51	8.4
	15-30	4.4	104	62	0.45	0.06	1.82	0.51	7.2
	30-45	4.4	107	63	0.45	0.06	1.71	0.53	6.9
Mean		**4.4**	**106**	**62**	**0.44**	**0.06**	**1.81**	**0.52**	**7.5**
Tine till	0-15	4.2	115	77	0.69	0.08	1.74	0.53	6.6
	15-30	4.2	110	74	0.60	0.07	1.83	0.52	6.3
	30-45	4.3	113	71	0.56	0.07	1.85	0.51	8.4
Mean		**4.2**	**113**	**74**	**0.62**	**0.07**	**1.81**	**0.52**	**7.1**
Min till	0-15	4.3	138	76	0.86	0.09	2.16	0.64	5.4
	15-30	4.3	116	65	0.68	0.07	2.14	0.65	6.3
	30-45	4.3	109	67	0.57	0.07	2.15	0.64	6.6
Mean		**4.3**	**121**	**69**	**0.70**	**0.08**	**2.15**	**0.64**	**6.1**
No till	0-15	4.0	126	102	0.80	0.08	2.44	0.62	6.4
	15-30	4.0	133	103	0.75	0.08	2.24	0.65	6.3
	30-45	4.0	134	95	0.72	0.08	2.37	0.64	6.3
Mean		**4.0**	**131**	**100**	**0.76**	**0.08**	**2.35**	**0.63**	**6.3**
Crop rotation									
Conv till	0-15	5.0	101	66	0.53	0.07	2.44	0.82	8.7
	15-30	4.8	98	71	0.65	0.07	2.21	0.84	8.2
	30-45	4.9	91	71	0.69	0.08	2.47	0.83	7.8
Mean		**4.9**	**97**	**69**	**0.62**	**0.07**	**2.37**	**0.83**	**8.2**
Tine till	0-15	4.3	138	87	0.93	0.10	2.17	0.68	7.6
	15-30	4.3	116	78	0.79	0.08	2.16	0.65	6.2
	30-45	4.3	118	75	0.79	0.08	2.20	0.67	7.0
Mean		**4.3**	**124**	**80**	**0.84**	**0.09**	**2.17**	**0.66**	**6.9**
Min till	0-15	4.3	106	72	0.82	0.09	1.81	0.56	6.7
	15-30	4.4	92	69	0.73	0.08	1.74	0.44	6.2
	30-45	4.5	92	62	0.60	0.07	1.63	0.55	6.2
Mean		**4.4**	**97**	**68**	**0.72**	**0.08**	**1.73**	**0.52**	**6.4**
No till	0-15	4.4	137	85	0.97	0.10	1.72	0.66	6.6
	15-30	4.5	121	78	0.79	0.09	1.69	0.68	6.5
	30-45	4.5	114	74	0.79	0.09	1.68	0.67	6.5

Mean		**4.5**	**124**	**79**	**0.85**	**0.09**	**1.69**	**0.67**	**6.5**

Generally, pH $_{KCl}$ was low (< 5.0) for all treatments (Table 1), in spite of a lime application of 2000 kg ha^{-1} during 2001 and 2005. Slightly higher soil pH values were shown for soil from the crop rotation system. Higher pH values were often found in crop rotation systems that include legume crops due to the reduced use of nitrogen fertilisers (Burle *et al*., 1997). This, however, cannot be the reason for the higher pH values in this study, as both the monoculture and crop rotation systems received the same fertiliser treatments. Conventionally tilled soil also showed slightly higher values compared to less intensive methods of soil tillage and especially the no-tilled plots, which confirms the results of studies in other parts of the world (Sprague & Triplett, 1986), where the lower pH in especially the top layers of no-tillage soil was ascribed to the build-up of organic material in these layers. In contrast to this, P and K tend to be higher when less intensive methods of soil tillage are used (Table 1). All P and K values were found to be sufficient for crop growth and were not expected to have any effect on crop growth and yield (Peverill *et al*., 1999).

Although the organic carbon content of the soil was generally low (< 1.0%), higher values were found in soil from the crop rotation system and where less intensive methods of tillage were applied (Table 1). Higher levels of soil organic C and total N, as well as lower concentrations of NO_3^--N can be directly related to surface accumulation of crop residues in systems of conservation tillage management (Salinas-Garcia *et al*., 1997). In contrast to the case in conventionally tilled soil, which is mixed by mouldboard ploughing, the content of organic C decreased with depth in the case of less intensive methods of tillage. These results are in agreement with the results of Agenbag & Maree (1989), Løpez-Fando & Almendros (1995) and Potter *et al*. (1997), who also found a significant increase in soil C in the topsoil with no tillage in comparison to conventional tillage and suggested increased mineralisation of the soil organic matter as a result of ploughing and soil mixing as the reason for this tendency.

Total N content showed higher values in the crop rotation system due to the nitrogen-fixing lupin crop grown in this system during 2007 (Table 1). Although a difference of only 0.01% was recorded between systems on average, it could account for a difference of more than 230 kg organic N per hectare in the 30 cm soil profile (bulk density of 1400 kg m^{-3}; gravel and stone content = 44.6%). Total N in less intensive methods of tillage also tended to be higher compared to conventionally tilled soil.

In the wheat monoculture system, calcium and magnesium tended to increase and sulphur tended to decrease with less intensive methods of tillage, but all three elements tended to decrease with less intensive methods of tillage in the crop rotation system (Table 1). All values were found to be sufficient for crop growth and are not expected to have any effect on crop growth and yield (Peverill *et al*., 1999).

Although some differences in micro-elements were found (Table 2), no clear trends were shown and all values, with the exception of those for B, which generally were low, were well above critical levels for crop growth (Peverill *et al*., 1999).

Table 2. Effect of soil tillage and crop rotation on soil micro-nutrients at Langgewens 2008

	Depth cm	Na mg kg^{-1}	Cu mg kg^{-1}	Zn mg kg^{-1}	Mn mg kg^{-1}	B mg kg^{-1}
Wheat monoculture						
Conv till	0-15	38	1.0	1.0	45	0.2
	15-30	31	0.9	1.1	46	0.2
	30-45	32	0.9	0.8	44	0.2
	Mean	**34**	**0.9**	**1.0**	**45**	**0.2**
Tine till	0-15	28	1.0	1.3	51	0.2
	15-30	23	1.0	1.1	54	0.2
	30-45	26	0.9	1.1	47	0.2
	Mean	**26**	**1.0**	**1.2**	**51**	**0.2**
Min till	0-15	27	1.0	1.6	23	0.2
	15-30	23	1.1	1.1	26	0.2
	30-45	23	1.1	1.0	24	0.2
	Mean	**24**	**1.1**	**1.2**	**24**	**0.2**
No till	0-15	23	0.5	0.9	34	0.3
	15-30	22	0.5	0.9	33	0.2
	30-45	22	0.5	0.9	37	0.2
	Mean	**22**	**0.5**	**0.9**	**35**	**0.2**
Crop rotation						
Conv till	0-15	58	2.2	2.0	42	0.3
	15-30	49	2.2	1.9	41	0.3
	30-45	51	2.2	1.8	39	0.3
	Mean	**53**	**2.2**	**1.9**	**41**	**0.3**
Tine till	0-15	30	0.7	1.3	57	0.2
	15-30	29	0.6	0.9	48	0.2
	30-45	29	0.7	1.0	48	0.2
	Mean	**29**	**0.7**	**1.1**	**51**	**0.2**
Min till	0-15	31	1.3	1.0	38	0.2
	15-30	28	1.3	0.9	32	0.2
	30-45	32	1.4	0.8	37	0.2
	Mean	**30**	**1.3**	**0.9**	**36**	**0.2**
No till	0-15	33	1.1	1.4	25	0.2
	15-30	30	1.1	1.3	23	0.2
	30-45	30	1.2	1.2	23	0.2
	Mean	**31**	**1.1**	**1.3**	**24**	**0.2**

N mineralisation

Mineral nitrogen (NH_4^+-N and NO_3^--N) in the 0 to 30 cm soil profile was measured at 30-day intervals from planting until the grain-filling stage at 120 days after planting (DAP) in the wheat crop following lupins (2008) and wheat crop following canola (2010). Only the plots that received 20 kg N ha^{-1} were measured and the results are presented in Table 3.

Table 3. Effect of soil tillage (ST) and crop rotation (CS) on mineral N content of the soil (mg NO_3-N + NH_4-N kg^{-1} soil) during the growing season of wheat at Langgewens in 2008 (after lupins) and 2010 (after canola)

	Year	Planting	30 DAP	60 DAP	90 DAP	120 DAP
Wheat monoculture						
Conv till	2008	38.48	32.62	26.08	21.50	15.10
	2010	36.10	27.20	23.10	19.67	14.10
	Mean	**37.29**	**29.91**	**24.59**	**20.59**	**14.60**
Tine till	2008	38.60	31.64	20.90	17.94	15.22
	2010	35.27	27.92	18.74	16.41	15.00
	Mean	**36.94**	**29.78**	**19.82**	**17.18**	**15.11**
Min till	2008	42.88	25.10	19.52	13.03	10.22
	2010	37.27	32.04	19.61	15.21	13.11
	Mean	**40.08**	**28.57**	**19.57**	**14.12**	**11.67**
No till	2008	46.46	32.56	21.27	15.71	12.21
	2010	40.01	34.22	24.17	19.22	13.10
	Mean	**43.24**	**33.39**	**22.72**	**17.47**	**12.66**
Crop rotation						
Conv till	2008	43.11	35.21	28.17	28.10	20.20
	2010	32.97	25.16	22.22	20.17	16.20
	Mean	**38.04**	**30.19**	**25.20**	**24.14**	**18.20**
Tine till	2008	40.17	32.19	25.22	26.19	19.47
	2010	33.75	30.08	22.41	19.80	14.13
	Mean	**36.94**	**31.14**	**23.82**	**23.00**	**16.80**
Min till	2008	44.17	30.19	27.47	31.21	27.51
	2010	36.72	30.18	24.95	20.58	17.51
	Mean	**40.45**	**30.18**	**26.21**	**25.90**	**22.51**
No till	2008	49.29	34.69	20.92	27.61	26.22
	2010	35.66	29.27	20.77	18.44	16.67
	Mean	**42.48**	**31.98**	**20.85**	**23.03**	**21.45**
LSD $_{T(P0.05)}$ =	**CS x ST**	**5.1**	**4.5**	**4.2**	**4.7**	**3.9**
	CS x ST x Year	**3.4**	**4.1**	**3.8**	**4.1**	**3.2**

In general, the mineral nitrogen content of the soil decreased from planting until 120 DAP for all methods of tillage. Although the response to different methods of tillage differed between different cropping systems (wheat monoculture vs. crop rotation), trends were not clear, most probably because the higher mineralisation rates generally found with conventional tillage (Sprague & Triplett, 1986) were offset by the higher organic C and total N contents (Table 1) measured in minimum and no-tillage plots.

However, the results from different years showed interesting trends. In the wheat monoculture system, differences between years were very inconsistent, with the exception of measurements at planting. In the crop rotation system, the mineral nitrogen content of the soil in the wheat crop following lupins (2008) was higher for all methods of tillage than in the wheat crop following canola (2010). This tendency was true throughout the growing season and clearly illustrates the effect of the nitrogen-fixing lupin crop on the supply of plant-available mineral nitrogen to the succeeding wheat crop, as is also shown by Armstrong *et al*. (1997). Higher values recorded in the minimum and no-tillage plots, compared to the conventional and tine-tilled plots, may be ascribed to a combination of the higher organic and nitrogen pool and a slower rate of nitrogen mineralisation with minimum and no tillage (Sprague & Triplett, 1986).

Crop yields

Lupin yield

The results (Table 4) show that lupin yields increased when less intensive methods of soil tillage were used. The highest yields were obtained when minimum and/or no tillage were used and the lowest yields were obtained when conventional mouldboard-based tillage or tine tillage was used.

Table 4 Effect of tillage on grain yield (kg ha^{-1}) of lupins during 2003 and 2007

	2003	**2007**	**Mean**
Conventional	1426	1842	1634
Tine	1464	2526	1995
Minimum (Min)	1777	2506	2142
Min / 2 x NT	14604	2428	1946
Min / 2 x NT	1910	2497	2204
Min / 3 x NT	2060	2253	2157
No till (NT)	1834	2289	2062
Mean	**1705**	**2334**	**2020**
LSD$_{T\ (P0.05)}$: Year 209 Tillage 186 Year x tillage 195			

Canola yield and oil content

Canola yields for the 2001, 2005 and 2009 cropping years were affected significantly as a result of the different methods of tillage used, but also showed a significant interaction with the rate of N fertiliser applied (Table 5). At low fertiliser rates (20 kg N ha^{-1}) and, to a lesser extent, also at 60 kg N ha^{-1}, conventional and tine tillage, which cause more soil disturbance, tend to result in higher yields when compared to minimum and no tillage. This was not the case at higher (100 kg N ha^{-1}) fertiliser rates, however, as all methods of tillage resulted in yields of about 1400 to 1500 kg ha^{-1}. Bonari *et al*. (1995) ascribed high yields with no-tilled rapeseed (*B. napus)* on sandy soil to the taproot systems of the rapeseed plant, which easily grow in compacted, untilled soil.

On average, canola yields increased from 872 kg ha^{-1} to 1 440 kg ha^{-1} when N application (rate and time) increased from 20 kg N ha^{-1} (applied at planting) to 100 kg N ha^{-1} (split between planting, 30 and 60 DAP). Ramsey & Callinan (1994) also found that canola yields responded positively to N fertilisers applied at either sowing or bud stage. Because canola yields did not tend to reach a plateau at application rates of 100 kg N ha^{-1}, higher rates should result in even higher yields. The agronomic efficiency of applied nitrogen, which varies between 6.15 and 8.05 kg yield increase per kilogram nitrogen applied at 20 to 60 and 60 to 100 kg N ha^{-1} respectively, also suggest that higher N rates should be considered.

Table 5 Effect of N application (kg N ha^{-1}) and method of tillage on grain yield (kg ha^{-1}) (mean for 2001, 2005 and 2009) and percentage oil (2009) of canola

	20 kg N ha^{-1}		**60 kg N ha^{-1}**		**100 kg N ha^{-1}**		**Mean**	
Tillage	**Yield**	**% Oil**	**Yield**	**% Oil**	**Yield**	**% Oil**	**Yield**	**% Oil**
Conv till	1060	41.3	1245	40.6	1461	40.3	1255	40.7
Tine till	1037	40.5	1378	40.1	1487	39.9	1301	40.2
Min till	733	41.2	987	39.5	1457	38.8	1059	39.8
Min/ NT	839	40.7	1024	39.7	1387	39.6	1083	40.0
Min/2 x NT	834	40.2	1087	40.2	1464	39.7	1128	40.0
Min/ 3x NT	728	40.2	1109	40.0	1436	39.7	1091	40.0
No till (NT)	872	41.8	995	41.4	1391	40.8	1086	41.3
Mean	872	40.8	1118	40.2	1440	39.8	1143	40.3

LSD$_{T\ (P0.05)}$:		**Yield**	**% Oil**
	Tillage	191	ns
	N rate	244	0.8
	T x N	219	ns

The oil content of the canola was measured in 2009 only (Table 5) and showed a significant response to nitrogen application rate, but not to method of tillage. The oil content (%) decreased from 40.8% to 39.8% with an increase in N application rate from 20 to 100 kg N ha^{-1}, most probably due to the well-known negative correlation between protein and oil content in canola seed (Ramsey & Callinan, 1994).

Wheat yield and protein content

During the period from 2001 to 2010, wheat yields in the wheat monoculture averaged 1 874 kg ha^{-1}, compared to a mean of 2 356 kg ha^{-1} where wheat was grown in rotation with lupins and canola (Table 6). However, yield increases due to crop rotation varied from 8.2% with conventional tillage to 33.4% with no tillage. The beneficial effect of crop rotation on wheat yield was therefore more pronounced when no tillage are practised instead of intensive conventional methods of tillage. In general, more intensive conventional tillage and, to a lesser extent, tine tillage resulted in higher yields compared to minimum and no-tillage systems where wheat was grown in monoculture. Differences in yield due to method of tillage where wheat was grown in rotation with lupins and canola were much smaller, and no tillage even tended to result in higher yields than conventional and tine tillage systems. Similar results were reported by Bellido *et al.* (1997) under Mediterranean-type climatic conditions.

Grain yields of wheat were also affected by the rates of nitrogen fertiliser applied, but responses differed for different crop rotations and methods of tillage used. In general, yields tend to be higher with increasing N fertiliser rates but, in contrast to the monoculture system, no significant differences in yield were shown between 60 and 100 kg N ha^{-1} if wheat was grown in rotation with lupins and canola. On average, agronomical use efficiencies of the N fertiliser tend to be higher in the monocropping system (4.88 kg increase in yield per kg of N applied) than in the crop rotation system (3.38 kg yield increase per kg N applied). These tendencies correlate with the higher N content of the soil and the resultant higher yield with low N application rates where lupins (Table 3) were included in the crop rotation system. These results indicate that planting a nitrogen-fixing lupin crop every fourth year is sufficient to reduce the N fertiliser requirements of preceding wheat crops, and this confirms the results shown in earlier studies (Armstrong *et al.*, 1997; Maali & Agenbag, 2003). Yield responses to N fertiliser rates generally were less pronounced where more intensive conventional and tine tillage systems were used. Grain protein content (%) showed an increase with higher N application rates in the crop rotation system, but not when wheat was grown in monoculture, because large increases in grain protein with higher N rates are only found when grain yield has reached or is near its maximum (Satorre & Slafer, 1999).

Table 6. Yield and quality response of wheat to different tillage methods (ST) and N fertiliser rates in two cropping systems (CS) at Langgewens (mean values for 2002, 2004, 2006, 2008 and 2010)

	Yield (kg ha^{-1})				**% Grain Protein**			
	20N	60N	100N	**Mean**	20N	60N	100N	**Mean**
Wheat monoculture								
Conv till	2071	2293	2465	**2276**	10.6	11.2	11.3	**11.0**
Tine till	1839	1943	2326	**2036**	10.5	10.9	11.0	**10.8**
Min till	1780	1805	1921	**1835**	10.2	10.5	10.9	**10.5**
Min/ NT	1432	1586	1800	**1606**	10.4	10.4	11.0	**10.6**
Min/ 2 x NT	1362	1524	1713	**1533**	10.5	10.7	10.7	**10.6**
Min/ 3 x NT	1618	1793	2198	**1870**	10.6	10.8	10.8	**10.7**
No till (NT)	1789	1900	2198	**1962**	10.4	10.8	10.7	**10.6**
Mean	**1699**	**1835**	**2089**	**1874**	**10.5**	**10.8**	**10.9**	**10.7**
Crop rotation								
Conv till	2398	2505	2484	**2462**	10.7	11.4	11.6	**11.2**
Tine till	2413	2423	2567	**2468**	10.5	10.9	11.4	**10.9**
Min till	2063	2410	2517	**2330**	10.3	10.8	11.3	**10.8**
Min/ NT	1958	2134	2320	**2137**	10.6	10.9	11.3	**10.9**
Min/ 2 x NT	1971	2184	2369	**2174**	10.5	10.6	11.0	**10.7**
Min/ 3 x NT	2162	2323	2427	**2304**	10.7	10.7	11.1	**10.8**
No till (NT)	2401	2575	2576	**2617**	10.6	10.7	10.9	**10.7**
Mean	**2195**	**2365**	**2465**	**2356**	**10.6**	**10.9**	**11.3**	**10.9**
LSD $_{T(P\ 0.05)}$								
CS	278				ns			
CS x N	254				0.6			
CSxSTxN	238				ns			

Dry mass production and yield components of wheat

To get a better understanding of the effect of tillage method on plant growth and yield in different cropping systems, dry mass yields as well as yield components were measured in

2008 and 2010. This was done by counting the number of plants m^{-2} and randomly sampling and dissecting 50 plants per plot.

The mean grain yield of 2 102 kg ha^{-1} obtained with wheat after lupins (2008) and wheat after canola (2010) was 37.8% higher than the 1 525 kg ha^{-1} obtained with wheat grown in monoculture (Table 7). To a large extent, the generally low yields obtained with wheat grown in monoculture and, to a lesser extent, with wheat grown in the crop rotation systems were due to very severe infestations of herbicide-resistant ryegrass (*Lolium* spp.), which competed with and thereby suppressed the growth and development of wheat plants (visual observations). This can be seen in the significantly lower number of ears m^{-2} in the monoculture system, while the number of plants m^{-2} was very similar to those in the crop rotation system (Table 7). Differences in number of ears m^{-2} between the monoculture and crop rotation systems were less pronounced with intensive conventional tillage than with minimum and no tillage, due to the ability to control weeds mechanically by mouldboard ploughing in conventional tillage systems (Sprague & Triplett, 1986; Børresen & Njøs, 1993).

Although the number of kernels ear^{-1} was not affected by method of tillage in the crop rotation systems, severe weed infestations with minimum tillage in the monoculture system resulted in lower yields and less kernels ear^{-1} (Table 7). Low yielding tillage systems in which minimum tillage was applied every second or third year also resulted in low thousand kernel weights (TKW) in the wheat monoculture system. On average, higher thousand kernel weights were produced by wheat grown in rotation with lupins and canola. These higher thousand kernel weights may to a large extent also be the result of less competition from weeds, but may due at least partly to the higher mineral N content of these plots towards the end of the growing season (Table 3). This higher supply of plant-available nitrogen and less competition from weeds may also be the reason for higher dry mass production where wheat was grown in rotation with lupins and canola (Table 7). In contrast to conventional tillage, less intensive tine, minimum and no tillage tend to have higher harvest indexes with crop rotation than in monoculture systems. This tendency may be due to the higher mineral N content at the end of the growing season, which prolongs the photosynthetic activity in leaves, improves the translocation of photosynthates to the kernels and hence results in a higher harvest index (Heenan *et al*., 1998).

Table 7. Effect of crop rotation and method of tillage on crop growth and yield of wheat at Langgewens (mean values for 2008 and 2010)

	Yield (kg ha^{-1})	Plants m^{-2}	Ears m^{-2}	Kernels ear^{-1}	TKW (g)*	DM gm^{-2}**	Harvest index (%)
Conv till	2039	160	180	34	33.6	5489	37.1
Tine till	1770	158	165	32	33.5	4990	35.4
Min till	1452	168	150	30	32.3	4242	34.3
Min/NT	1107	163	135	30	28.4	3287	33.7
Min/ 2xNT	1263	154	137	30	31.7	3587	35.2
Min/3xNT	1485	158	140	32	32.1	4021	36.9
No till (NT)	1570	162	148	34	31.2	4441	35.4
Mean	**1525**	**160**	**150**	**32**	**31.8**	**4294**	**35.4**
Crop rotation							
Conv till	2129	154	180	34	33.8	5670	37.5
Tine till	2170	162	181	34	35.3	5619	38.6
Min till	2070	149	177	32	36.8	5614	36.8

Min/NT	1893	152	170	32	34.8	5176	36.6
Min/2xNT	1952	157	180	32	33.9	5308	36.7
Min/3xNT	2163	161	183	34	37.2	5722	37.8
No till (NT)	2337	162	187	34	37.0	6076	38.4
Mean	**2102**	**157**	**179**	**33**	**35.5**	**5598**	**37.5**
LSD $_T$(0.05)							
CR	207	ns	19	ns	2.8	726	ns
CRxST	294	ns	32	4	3.1	770	3.8

* Thousand kernel weight
**Above ground DM at harvest

CONCLUSIONS

In this study, minimum and no tillage outyielded conventional mouldboard-based tillage and can therefore be used successfully to produce spring-type canola, lupin and wheat crops in sustainable crop rotation systems under rain-fed conditions in the Swartland wheat-producing area of the Western Cape province of South Africa. Higher wheat yields when grown in a crop rotation system compared to a monoculture system can be ascribed to less problems with grassy weeds, but also to improved soil organic C and nitrogen contents, which result in more plant-available mineral nitrogen and hence more vigorous crop growth. Grain yields of wheat and canola crops responded positively to increased N application rates, and the results suggest that application rates of more than 100 kg ha^{-1} should be considered. Higher nitrogen application rates resulted in higher grain protein and hence improved bread-making quality of the wheat, but oil content and thus the quality of canola tend to decrease with higher N application rates.

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