Annegret Übelhör, Irene Witte, Norbert Billen, Sabine Gruber, Wilfried Hermann, Jörg Morhard, Wilhelm Claupein

Feasibility of strip-tillage for field grown vegetables

Eignung des Strip-Tillage Verfahrens für den Feldgemüsebau

Abstract

Row crops and field grown vegetables, such as white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*), are affected by soil erosion caused by rainfall energy. Conservation tillage, such as strip-tillage, is the most effective way to reduce soil erosion. Hence, the objectives of this study were to develop and modify the strip-tillage system for white cabbage and lettuce (*Lactuca sativa* var. *capitata* L.), and to assess its potential towards controlling soil erosion. In 2011 and 2012 rainfall simulations showed significantly lower soil loss under strip-tillage (ST) than under the moldboard plow (MP). Soil loss under MP was 512 g m^{-2} in 2011 and 210 g m^{-2} in 2012, while ST reduced soil loss by 80% in 2011 and 90% in 2012. The ST sampling positions for soil property assessments were in the non-tilled zone i.e. between the planting row (ST_BR) and the tilled zone, within the planting row (ST_IR). Top soil bulk density (0-10 cm) was lowest in ST_IR (1.24 g cm^{-3}), followed by MP (1.33 g cm^{-3}) and ST_BR (1.53 g cm^{-3}). Penetration resistance in the top soil was also lowest in ST_IR followed by MP and ST_BR. Plant available water [L m^{-2}] from 0–40 cm was higher in ST_BR compared to MP and ST_IR. In 2011 average cabbage head weight was not affected by tillage treatment. In 2012 the cabbage head weight was significantly higher in ST (1.85 kg) than in MP (1.62 kg). The results show that strip-tillage can be a viable option for crops which are exposed to an erosion risk, such as white cabbage.

Key words: White cabbage, *Brassica oleracea* convar. *capitata* var. *alba*, Conservation tillage, RTK-GPS, Soil erosion, Gravimetric water content, Bulk density, Penetration resistance

Zusammenfassung

Gemüsekulturen mit einem weiten Reihenabstand, wie beispielsweise Weißkohl (*Brassica oleracea* convar. *capitata* var. *alba*) sind bei Starkniederschlägen einem hohen Erosionsrisiko ausgesetzt. Konservierende Bodenbearbeitungsverfahren wie das Strip-Tillage Verfahren können die Gefahr der Bodenerosion reduzieren. Aus diesem Grund wurde in den Jahren 2011 und 2012 in einem Feldversuch in Südwestdeutschland das Erosionsschutzpotential des Strip-Tillage Verfahrens in Kopfsalat (*Lactuca sativa* var. *capitata* L.) und Weißkohl geprüft und untersucht, ob das Verfahren eine Alternative zur konventionellen, wendenden Bodenbearbeitung mit dem Pflug darstellen kann. Bei Beregnungsversuchen konnte gezeigt werden, dass der Bodenabtrag im Strip-Tillage Verfahren (ST) im Vergleich zur konventionell bearbeiteten Pflugvariante (MP) signifikant geringer war. Die Bodenabträge lagen nach einer Beregnungsmenge von 40 Litern in 20 Minuten in MP im Jahr 2011 bei 512 g m^{-2} und 2012 bei 210 g m^{-2}. Im Vergleich hierzu waren die Bodenabträge in ST 2011 um 80% und 2012 um 90% geringer als in MP. Für die bodenkundlichen Untersuchungen wurde in den Strip-Tillage Parzellen sowohl im bearbeiteten Bereich, innerhalb der Pflanzreihe (IR), als auch im unbearbeiteten Bereich, zwischen den Pflanzreihen (BR) gemessen. Die Lagerungsdichte im Oberboden (0–10 cm) war in ST_IR (1,24 g cm^{-3}) am geringsten gefolgt von MP (1,33 g cm^{-3}) und ST_BR (1,53 g cm^{-3}). Beim Eindringwiderstand im Oberboden wurden ebenfalls die geringsten Werte in ST_IR und die höchsten in MP gemessen. Die Menge an pflanzenverfügbarem Wasser [L m^{-2}] von 0–40 cm Bodentiefe war in ST_BR höher als in MP und ST_IR. Im Jahr 2011 wurde kein signifikanter Unterschied im durch-

Institute
University of Hohenheim, Institute of Crop Science (340a), Stuttgart, Germany

Correspondence
Dipl. agr. biol. Annegret Übelhör, University of Hohenheim, Institute of Crop Science (340a), Fruwirthstr. 23, 70599 Stuttgart, Germany, E-Mail: Annegret.Uebelhoer@uni-hohenheim.de

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schnittlichen Kopfgewicht zwischen MP und ST gemessen. 2012 wurde in ST mit durchschnittlich 1,85 kg ein signifikant höheres Kopfgewicht als in MP (1,62 kg) festgestellt. Somit kann das Strip-Tillage Verfahren für erosionsanfällige Kulturen wie Weißkohl eine Alternative zum konventionellen Pfluganbau darstellen.

Stichwörter: Weißkohl, *Brassica oleracea* convar. *capitata* var. *alba*, Konservierende Bodenbearbeitung, RTK-GPS, Bodenerosion, gravimetrischer Wassergehalt, Lagerungsdichte, Eindringwiderstand

Introduction

Soil erosion by water and wind is a widespread global problem, primarily due to the application of intensive agricultural production systems, and specifically due to inversion tillage with the moldboard plow, deforestation, and overgrazing (Yassoglou et al., 1998). Soil erosion is exacerbated when rain falls on steep slopes or on erosion-prone soils. In the central and northwestern regions of Europe, the soil erosion risk is less severe than in the south because of more gentle slopes and more evenly dispersed rainfall throughout the year. Regardless of these factors, intensively cultivated arable land in central and northwestern Europe could also be at risk of erosion (Grimm et al., 2002). The cultivation of spring crops grown in wide rows such as maize, sugar beet, and field grown vegetables, requires fine seedbed preparation and thus more intensive soil preparation, which consequently raises the soil erosion risk (Bielders et al., 2003). Regions with loess soils having high silt content are especially vulnerable to surface runoff and soil erosion. Areas in northwestern Europe that are characterized by such soils, include, among others, two regions in Belgium around Limbuorg and the Belgium loess belt, and the French region "Pay de Caux" (Boardman et al., 1994). An example of an erosion-prone area in Central Europe is the "Filderebene", in the southwest of Germany. The Filderebene is characterized by fertile soils with a loess layer, prevalent soil types are Cambisol and Luvisol derived from periglacial loess. The region is known as a large vegetable production region. In recent years this region has suffered damage by heavy rainfall that washed away plantlets and decreased yields. Furthermore, off-site damages from silty or flooded roads are quite common. Due to such problems, in the beginning of 2010 the Baden-Wuerttemberg Ministry of Rural Affairs and Consumer Protection established the project "Development of Erosion Control Strategies for Field Grown Vegetables". This project aimed to develop erosion control strategies for vegetable producers in accordance with the Federal Soil Protection Act and the soil erosion register according to the Cross Compliance regulation (Lubw, 2011). Therein, the time period allowing for inversion tillage (e.g. moldboard plowing) is fixed according to the slope and other properties defining the erosion risk as per the Universal Soil Loss Equation (Wischmeier and Smith, 1978). On fields prone to erosion and for row crops with a planting distance of more than 45 cm, moldboard plowing is prohibited over winter time. White cabbage and many other field grown vegetables fall into this category. Hence, vegetable producers need a non-inversion tillage option for producing vegetables on erosion-prone soils.

One option for non-inversion tillage might be the strip-tillage or zone-tillage technique, which has been gaining attention in maize and sugar beet production (Overstreet, 2009). Strip-tillage aims to unify the advantages of conventional tillage (moldboard plow) and no-till systems (Vyn and Raimbault, 1993). For vegetable crops, especially transplants such as cabbage, there are hardly any reduced tillage options because there is no suitable technical solution on the market yet, and the strip-tillage technique might be a better solution than other reduced tillage methods. This is because the plantlets are dependent on a finely crumbled, homogeneous seedbed for good growing conditions which strip-tillage can create in the tilled strips.

In general, non-inversion tillage, including strip-tillage, shows several beneficial effects in terms of reducing soil erosion risks (Withers et al., 2007; Raczkowski et al., 2009): keeping 50–75% of the residues from the previous crop on the soil surface protects the soil from direct exposure to rainfall energy. Additionally, strip-tillage is assumed to change soil physical properties such as increased water infiltration, water storage, soil temperature, and soil organic matter. In conservation tillage systems, infiltration rates are often higher while bulk density, penetration resistance and soil losses are often lower than in conventional tillage (Thierfelder and Wall, 2009; Stavi et al., 2011).

The objective of this study was to develop a strip-tillage system for vegetable transplants. Lettuce (*Lactuca sativa* var. *capitata* L.) and white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*) were cultivated in field experiments with strip-tillage equipment, which was modified for vegetable transplants. The model experiments, including a portable small rainfall simulator, intended to demonstrate the erosion control potential of the strip-tillage system. Soil mineral nitrogen, bulk density, penetration resistance and the water regime of strip-tillage plots were compared to moldboard plowed treatments. The yield potential of the new tillage technology was determined and should clarify whether strip-tillage is a non-inversion tillage option for field grown vegetables.

Material and Methods

Site description and weather conditions

The field experiments were conducted at the research station Ihinger Hof (48°44′N, 8°55′E, 478 m a.s.l., Southwest-Germany). The average annual precipitation is 691 mm and the average annual temperature 8.3°C. The precipitation in 2011 was 591 mm and in 2012 658 mm (Fig. 1). The months with the highest precipitation intensities during the growing season were June and July. The

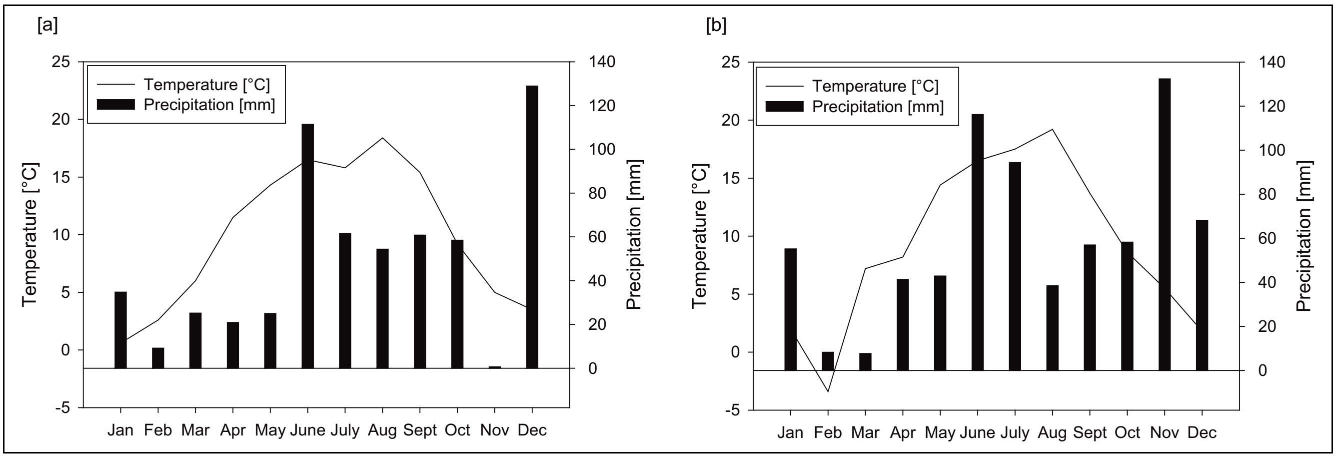

Fig. 1. **Monthly average temperature and precipitation in 2011 [a] and 2012 [b] at Ihinger Hof**
Monatliche mittlere Temperaturen und Niederschläge 2011 [a] und 2012 [b] am Ihinger Hof

soil type was a Haplic Cambisol Ruptic (Loess above Upper Trassic). In the upper layer (0–20 cm) the soil texture was a silt loam (SiL) and the second layer (below 20 cm) represented loam (FAO,, 2006). The mean slopes of the fields were 7.3% (2011) and 8.8% (2012), respectively.

Experimental design and treatments

The experimental design was a randomized complete block design with four treatments and four replicates of 6 m × 20 m per plot. The prior cereal crop to the field grown vegetables in both years was winter triticale cv. Talentro, conventionally tilled by moldboard plow and rotary harrow. The 2011 treatments included (i) moldboard plowing without lettuce as the previous crop in spring (MP), (ii) moldboard plowing with lettuce as the previous crop in spring (MP_lettuce), (iii) strip-tillage without lettuce as the previous crop in spring (ST), and (iv) strip-tillage with lettuce as the previous crop in spring (ST_lettuce). Treatments were prepared using strip-tillage equipment (Horsch; prototype: Focus, Schwandorf, Germany) and a moldboard plow in autumn in both experimental years. Furthermore, stubble tillage after triticale harvest was conducted in the conventionally tilled treatments (Tab. 1). The strip-tillage machine had a working width of 3 m with 6 tines for strip preparation. The tilled rows were 20 cm deep and 20 cm wide. On 15

Tab. 1. **Treatments and tillage operations. Stubble tillage by Dyna-Drive, 5–10 cm deep. Seedbed preparation by rotary harrow or strip-tiller**
Versuchsvarianten und Bodenbearbeitungsmaßnahmen. Stoppelbearbeitung mit Dyna Drive, 5–10 cm tief. Saatbettbereitung mit Kreiselegge oder Strip-Tiller

Treatments (Abbreviation)	Stubble tillage	Tillage operation in autumn	Seedbed preparation in spring
2011			
Moldboard plowing without lettuce as previous spring crop (MP)	Yes	Moldboard plowing[1]	Yes[3]
Moldboard plowing with lettuce as previous spring crop (MP_lettuce)	Yes	Moldboard plowing[1]	Yes[3]
Strip-tillage without lettuce as previous spring crop (ST)	No	Strip-tillage[2]	No
Strip-tillage with lettuce as previous spring crop (ST_lettuce)	No	Strip-tillage[2]	No
2012			
Moldboard plowing (MP)	Yes	Moldboard plowing[1]	Yes[3]
Strip-tillage (ST)	No	Strip-tillage[2]	No
Intensive strip-tillage with placed nitrogen fertilization (ST_Int_bN)	Yes	Strip-tillage[2]	Yes[4]
Intensive strip-tillage with broadcast nitrogen fertilization (ST_Int_pN)	Yes	Strip-tillage[2]	Yes[4]

[1] 25 cm deep
[2] 20 cm deep
[3] rotary harrow
[4] second, shallow loosening with strip-tiller (5 cm deep)

Apr. 2011, lettuce cv. Gisela was transplanted in eight plots (MP_lettuce, ST_lettuce) of the established trial (four strip-tillage and four moldboard plowed plots) at 0.35 m in-row spacing and 0.5 m inter-row spacing. After the lettuce harvest in June 2011, white cabbage cv. Marcello was transplanted at 0.5 m in-row spacing and 0.5 m inter-row spacing in each treatment (Tab. 2). Thereby, for cabbage cultivation the same rows were used as for lettuce without any further soil preparation or removal of lettuce residues. In 2012, soil preparation was similar to 2011. The treatments were modified to further adopt the system. Moldboard plowing (MP) and strip-tillage (ST) remained unchanged to guarantee the comparability of the two experimental years. Furthermore, intensive strip-tillage with broadcast nitrogen fertilization (ST_Int_bN) and intensive strip-tillage with band-placed N fertilizer (ST_Int_pN) was introduced instead of heaving treatments with and without lettuce before cabbage (Tab. 1). Intensive strip-tillage, which was characterized by a second 5 cm deep strip-tillage pass, was conducted to loosen the strips in spring 2012 one day prior to transplanting white cabbage (Tab. 3). Additionally to MP, in the intensive strip-tillage treatments, stubble tillage was conducted after triticale harvest.

White cabbage was transplanted with a total-control transplanter from Checchi & Magli (Type TRIUM, Budrio, Italy). The machine was modified by installing row-cleaners in front of special blades for mulch-planting systems. The row-cleaners clear the planting rows from straw residue and large soil clods to achieve an exact planting result.

Both the strip-tiller and planting machine were equipped with a device for placed nitrogen fertilizer application during strip-tillage and transplanting. The fertilizer granules were placed 5 cm deep exactly in the planting row. Furthermore, for the strip-tillage and the transplant processes, an RTK-GPS auto-guidance system was used with the precision of 2.5 cm to make sure that plantlets and fertilizer was placed in the targeted position.

Soil mineral nitrogen and fertilization

Soil mineral nitrogen (SMN) samples were taken in all treatments with a core sampler at depths of 0–30 cm, 30–60 cm and 60–90 cm, both in-row and between planting rows. Samples for SMN were taken before transplanting in spring (7 Apr. 2011, 10 Apr. 2012) and after harvest in both years (19 Sept. 2011, 15 Aug. 2012). Sampling position was at hill slope and foot slope within each plot. The soil samples were dried for 24 h at 105 °C. SMN was analyzed by flow injection in accordance with VDLUFA standards (ISO, 13395, 1996) with a nitrogen analyzer FIAstar™ 5000 (Tecator, Foss, Rellingen, Germany).

Spring time nitrogen fertilization was based upon SMN target values for lettuce and white cabbage. For lettuce 150 kg N ha^{-1} and for white cabbage 270 kg N ha^{-1} were applied. The 2012 nitrogen fertilizer rate was split for placed nitrogen application (ST_Int_pN). The first half was applied with the second strip-tillage pass in spring and the second nitrogen rate was applied while transplanting white cabbage. For MP and the non-intensive ST treatment, the nitrogen fertilizer was applied broadcast

Tab. 2. Field management, plant protection and soil tillage treatments in 2011
Bodenmanagement, Pflanzenschutz- und Bodenbearbeitungsmaßnahmen 2011

Date	Tillage system	Process (tillage, plant protection, transplanting, harvesting)
29 Oct. 2010	MP[1,2]	Soil preparation with moldboard plow
29 Oct. 2010	ST[3,4]	Strip-tillage with prototype strip-tiller
24 Mar. 2011	MP/ST[1,2,3,4]	Glyphosate application (herbicide)
14 Apr. 2011	MP[1,2]	Seedbed preparation with rotary harrow
15 Apr. 2011	MP/ST[2,4]	Transplanting lettuce cv. Gisela
09 June 2011	MP/ST[2,4]	Lettuce harvest
10 June 2011	ST[3,4]	Glyphosate application (herbicide)
21 June 2011	MP[1,2]	Rotary harrow
21 June 2011	MP/ST[1,2,3,4]	Transplanting white cabbage cv. Marcello
28 June 2011	MP/ST[1,2,3,4]	Metaldehyde application (molluscicide)
06 July 2011	MP/ST[1,2,3,4]	Metazachlor + Quinmerac application (herbicide), Alphacypermethrin application (insecticide)
12 July 2011	MP/ST[1,2,3,4]	Dimethoate application (insecticide), paraffin oil application (insecticide), Clethodim application (herbicide)
16 Sept. 2011	MP/ST[1,2,3,4]	White cabbage harvest

[1] Moldboard plowing (MP)
[2] Moldboard plowing with lettuce as previous crop (MP_lettuce)
[3] Strip-tillage (ST)
[4] Strip-tillage with lettuce as previous crop (ST_lettuce)

Tab. 3. Field management, plant protection and soil tillage treatments in 2012
Bodenmanagement, Pflanzenschutz- und Bodenbearbeitungsmaßnahmen 2012

Date	Tillage system	Process (tillage, plant protection, transplanting, harvesting)
26 Sept. 2011	ST[2,3,4]	Strip-tillage with prototype strip tiller
02 Nov. 2011	MP[1]	Soil preparation with moldboard plow
25 Apr. 2012	ST[2,3,4]	Glyphosate application (herbicide)
30 Apr. 2012	MP[1]	Seedbed preparation with rotary harrow
30 Apr. 2012	ST[3,4]	Second pass with strip tiller
02 May 2012	MP/ST[1,2,3,4]	Transplanting white cabbage cv. Marcello
04 May 2012	MP/ST[1,2,3,4]	Metaldehyde application (molluscicide)
30 May 2012	MP/ST[1,2,3,4]	Pendimethalin application (herbicide), Clopyralid + Picloram application (herbicide), Thiacloprid application (insecticide)
28 June 2012	MP/ST[1,2,3,4]	Alphacypermethrin application (insecticide)
09 Aug. 2012	MP/ST[1,2,3,4]	White cabbage harvest

[1] Moldboard plowing (MP)
[2] Strip-tillage (ST)
[3] Intensive strip-tillage intensive with broadcast nitrogen fertilization (ST_Int_bN)
[4] Intensive strip-tillage with placed nitrogen fertilization (ST_Int_pN)

one day prior to transplanting. For cabbage, potassium and magnesium sulfate were applied via broadcast if necessary, in accordance with official fertilizer recommendations.

Rainfall simulation
Soil loss by water erosion was artificially induced by a small rainfall simulator in an area of 1 m^2, according to the construction of ZIMMERLING (2004). In 2011, the rainfall experiment was conducted in MP_lettuce and ST_lettuce treatments, 3 days after transplanting. In 2012, rainfall simulation was done in white cabbage crop in three replicates of MP, ST and ST_Int_bN. A metal frame (1 m^2) was driven 10 cm deep into the soil. The irrigation area always included 2 planting rows. This implies that in strip-tillage plots, 40% of the irrigation area was tilled and 60% was undisturbed and covered with straw residues. Water (2 mm min^{-1}) was applied to the 1 m^2 metal framed plot from a 2 m high nozzle, which homogenously distributed the water over the plot area. During the rainfall simulation, the equipment was covered by plastic shelter to reduce the effect of wind on droplet dispersion. The runoff samples were collected in 2 L PET-bottles, which were changed every minute. The rainfall simulation was conducted for 20 minutes per plot. To quantify the soil- water suspension in the bottles after rainfall simulation, the bottle's tare weight was subtracted from filled bottles. The suspension was shaken; subsamples were taken immediately and subsequently dried at 105 °C. Soil loss was determined according to:

$$\text{soil loss}[g] = \frac{\text{weight of dry soil}[g]}{\text{weighed out suspension}[g]} \times \text{suspension in bottles}[g] \quad [1]$$

Soil characteristics and crop yield
For determination of bulk density five 100 cm^3 soil cores were taken in MP and ST in one plot per treatment at the foot of the slope from the depths of 10 cm, 30 cm and 40 cm. Strip-tillage (ST) sampling positions were in the tilled zone (ST_IR) and between planting rows in (ST_BR). Samples were taken on 9 June 2011. Soil sample cores were dried for 72 h at 105 °C and subsequently weighed. Bulk density was calculated by relating dry matter in g to the volume of the soil sample core.

An Eijkelkamp Penetrologger was used to measure penetration resistance down to a depth of 50 cm on 15 May 2011 in all MP_lettuce and ST_lettuce plots with ten measurements taken per plot. For ST_lettuce, measurement samples were taken again both in the planting rows (IR) and between the planting rows (BR).

Disturbed soil samples were taken on five dates between June and August 2011 during white cabbage cultivation to determine the gravimetric water content. All MP and ST plots were sampled with a soil core sampler (1 cm inner diameter) at 0–10 cm, 10–30 cm and 30–40 cm depths. Strip-tillage sampling positions were in row (ST_IR) and between rows (ST_BR). Positions for sampling within each plot corresponded to the hill slope, with the components of the back slope, and the foot slope. In each plot, two samples were taken per position and depth. Soil samples were dried at 105 °C for 24 h and gravimetric water content was calculated by the mass difference of wet soil and dry soil weight.

Plant-non-available water content was measured, corresponding to the bulk density, in one plot per treatment and at 10 cm, 30 cm and 40 cm depths (data not shown). The plant available water content [L m^{-2}] was calculated by multiplying the gravimetric water content by the soil horizon thickness and the bulk density. Plant-non-available water content was subtracted. Subsequently, the sum was calculated for all values from each depth within each treatment.

In 2011, lettuce and white cabbage were harvested after 55 days and 118 days, respectively. In 2012, white cabbage was harvested 98 days after transplanting.

Three field transects were harvested with 18 plants per plot. In total, 288 white cabbage plants were cut per year. Whole cabbage plants were harvested and weighed. Subsequently, all cover leaves were removed and the head fresh weight was determined.

Statistical analysis

Statistical analyses were performed using PROC MIXED with SAS Software (SAS, 2004). Before analysis of variance was conducted, normal distribution was tested for all data sets. All 2011 data sets were analyzed according to a randomized complete block design (RCBD) with two tillage treatments (T), two previous crops (PC) and three sampling positions (Pos) in four replicates (R) on each plot (P). The model in syntax of Patterson (1997) is given by:

$$T + PC + PC{\cdot}T + R: P + Pos,$$

where fixed effects are given before and random effects are given after the colon, and interactions by a dot between the corresponding main effects. In 2012 different previous crops (PC) were replaced by different N fertilizer application systems (N). For soil mineral nitrogen, gravimetric water content and penetration resistance at different soil depths (D) and repeated core sampling at the same position (rPos) were assumed. The model is given by:

$$R + T + D + T{\cdot}D: P{\cdot}D + P{\cdot}Pos{\cdot}D + P{\cdot}Pos{\cdot}rPos{\cdot}D,$$

again with fixed effects given before and random effects given after the colon, and interactions by a dot between the corresponding main effects. For bulk density, the model syntax was adjusted due to lack of field replicates.

For residual error effects of depth (D) a joint variance structure was assumed because of the existing autocorrelation effect of the different soil depths.

Different sampling dates of soil mineral nitrogen and gravimetric water content were separately analyzed from each other. For letter description, a multiple t-test was used only after finding significant differences via an F-test.

Results

Soil mineral nitrogen

Soil mineral nitrogen (SMN) content after the 2011 spring lettuce harvest averaged between 16 and 24 kg N ha^{-1}. At white cabbage harvest in 2011, SMN contents ranged between 1.5 and 3.7 kg N ha^{-1} (Tab. 4). There were no significant differences in SMN contents either in spring or after harvest. The 2012 treatments similarly did not significantly differ in SMN in spring and autumn.

Rainfall simulation

In 2011, there was a highly significant difference between cumulative soil losses in ST_lettuce (104 g m^{-2}) and MP_lettuce (512 g m^{-2}). In MP_lettuce, soil loss was increasing from the sixth minute of the irrigation proce-

Tab. 4. Soil mineral nitrogen (0–90 cm) in different tillage treatments (see Tab. 1) in spring before planting and after harvest (autumn) of white cabbage in 2011 and 2012. IR: sampling position within tilled planting row, BR: sampling position in non-tilled zone between planting rows. There are no significant differences between the treatments (n.s.), P < 0.05. Comparison only within sampling dates

N_{min}-Gehalte des Bodens (0–90 cm) bei unterschiedlichen Bodenbearbeitungsverfahren (vgl. Tab. 1) im Frühjahr vor dem Pflanzen und im Herbst nach der Ernte von Weißkohl 2011 und 2012. IR: Probenahme innerhalb der bearbeiteten Pflanzreihe, BR: Probenahme im unbearbeiteten Zwischenreihenbereich. Keine signifikanten Unterschiede zwischen Behandlungen (n.s.), P < 0,05. Vergleiche nur innerhalb von Probenahmeterminen

	Spring 2011	Autumn 2011		Spring 2012	Autumn 2012
	Soil mineral nitrogen (kg N ha^{-1})				
Treatment and sampling position	n.s.	n.s.	Treatment and sampling position	n.s.	n.s.
MP	20.17	2.32	MP	5.83	1.35
MP_lettuce	23.86	1.48	ST_IR	8.50	1.51
ST_IR	15.66	3.32	ST_BR	8.16	1.35
ST_BR	16.54	2.26	ST_Int_bN_IR	7.63	1.73
ST_lettuce_IR	19.22	3.61	ST_Int_bN_BR	6.61	1.10
ST_lettuce_BR	22.02	3.50	ST_Int_pN_IR	n.d.[1]	1.09
			ST_Int_pN_BR	7.01	1.13

[1] not determined

dure until 20 minutes had past. In ST_lettuce, soil loss started two minutes later than in MP_lettuce (Fig. 2a). In 2012, soil loss was 20 g m^{-2}, 110 g m^{-2} and 210 g m^{-2} in ST, ST_Int_bN and MP, respectively; however, cumulative soil loss was not significantly different. Soil erosion commenced in the fifth minute of the irrigation in MP and ST_Int_bN, whereas in ST soil erosion started in the eighth minute of irrigation (Fig. 2b). Generally, soil losses in 2012 were considerably lower than in 2011.

Bulk density and penetration resistance

Bulk density was measured in 2011 only. The statistical analysis of the bulk density showed interactions between treatment and depth (Tab. 5). At 10 cm soil depth, the lowest bulk density was measured in ST_IR followed by MP and ST_BR. At a depth of 30 cm, the bulk density of MP and ST_IR was significantly lower than ST_BR. At 40 cm soil depth, the bulk density did not differ significantly. In MP and ST_IR, the bulk density increased significantly with soil depth. In ST_BR, the bulk density increased from 10 cm to 30 cm but decreased from 30 cm to 40 cm soil depth (Tab. 6).

The penetration resistance was proportional to bulk density. In the tilled soil layer, the highest penetration resistance was measured at a depth of 7 cm in ST_lettuce_BR (1.76 MPa; Fig. 3). The penetration resistance values in ST_lettuce_IR were lower from 0 cm to a depth of 14 cm than under MP_lettuce and ST_lettuce_BR. At 7 cm ST_lettuce_IR and ST_lettuce_BR differed significantly. Penetration resistance decreased in MP_lettuce and ST_lettuce_BR from 7 cm to 17 cm respectively, in ST_lettuce_IR from 7 cm to 14 cm followed by increased values down to 30 cm depth. From 16 cm to 50 cm, penetration resistance was not affected by tillage treatment, previous crop or sampling position.

Gravimetric water content and plant available water in soil

Interactions occurred between treatment and soil depth across all dates (Tab. 7). Gravimetric water content ranged from 16.8% to 24.2% over the entire cultivation period (Tab. 8). Lowest gravimetric water content was detected in MP from 0–10 cm soil depth over the entire growing period, except 25 July 2011. Significantly higher

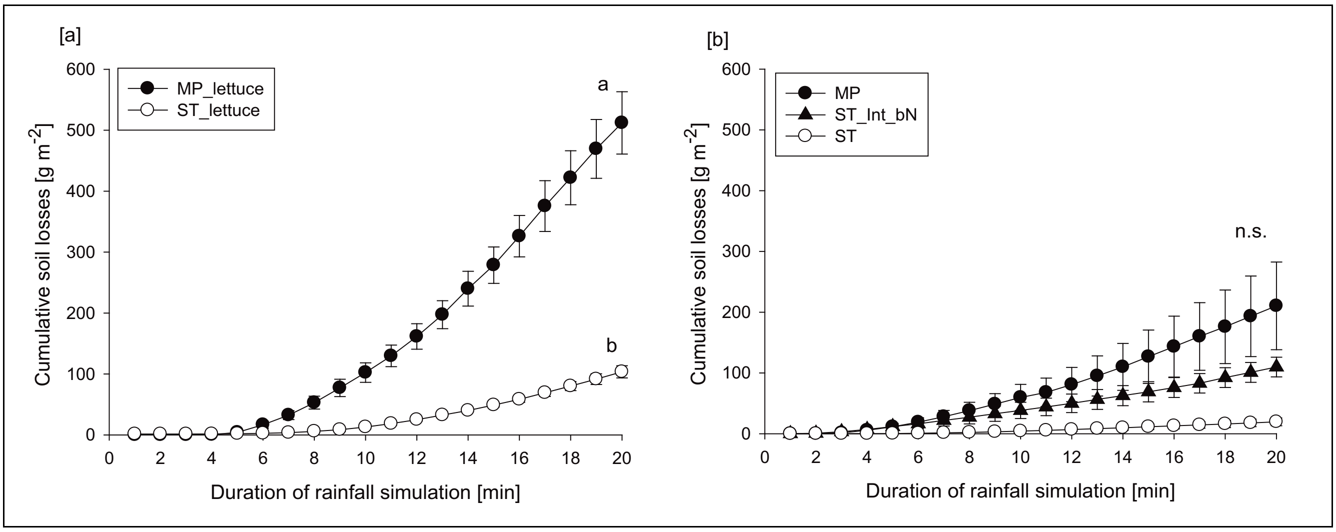

Fig. 2. **Cumulative soil loss [g m^{-2}] during 20 min of simulated rainfall (2 L min^{-1}) in [a] 2011 and [b] 2012. MP_lettuce: moldboard plowing with lettuce as previous crop, ST_lettuce: strip-tillage with lettuce as previous crop, MP: moldboard plowing, ST: strip-tillage, ST_Int_bN: intensive strip-tillage with broadcast nitrogen fertilization. Identical letters show no significant differences, *P* < 0.05. Error bars indicate the standard errors of means.**

Kumulativer Bodenabtrag [g m^{-2}] während 20minütigem simulierten Regen (2 L min^{-1}) 2011 [a] und 2012 [b]. MP_lettuce: Pflug, Vorfrucht Kopfsalat, ST_lettuce: Strip-Tillage, Vorfrucht Kopfsalat, MP: Pflug, ST: Strip-Tillage, ST_Int_bN: Intensives Strip-Tillage mit breit gestreuter N-Düngung. Gleiche Buchstaben zeigen nicht signifikante Unterschiede, P < 0,05. Fehlerbalken sind Standardfehler des Mittelwerts.

Tab. 5. Table of variance for bulk density [g cm^{-3}] in 2011 for different tillage treatments and soil depths

Varianztabelle der Lagerungsdichte [g cm^{-3}] 2011 für die Faktoren Bodenbearbeitung und Bodentiefe

Effect	DF	F-value	Pr > F
Treatment	2	22.16	0.0028
Depth	2	31.53	< 0.0001
Treatment × depth	4	13.64	< 0.0001

Tab. 6. Bulk densities [g cm^{-3}] measured in 2011 under different tillage treatments and sampling positions. MP: moldboard plowing, ST_IR: strip-tillage measured in planting rows, ST_BR: strip-tillage measured between planting rows. Data with the same letter are not significantly different; lower case letters refer to individual columns, upper case letters to rows, P < 0.05
Lagerungsdichte [g cm^{-3}] 2011 in Abhängigkeit von Bodenbearbeitung und Probenahmeposition. MP: Pflug, ST_IR: Strip-Tillage in der Pflanzreihe, ST_BR: Strip-Tillage zwischen Pflanzreihen. Gleiche Buchstaben zeigen nicht signifikante Unterschiede; Kleinbuchstaben gelten innerhalb der Spalte, Großbuchstaben innerhalb der Zeile, P < 0,05

Treatment_position	10 cm	30 cm	40 cm
	Bulk density (g cm^{-3})		
MP	1.33$^{b\ C}$	1.47$^{b\ B}$	1.53$^{a\ A}$
ST_IR	1.24$^{c\ C}$	1.47$^{b\ B}$	1.51$^{a\ A}$
ST_BR	1.53$^{a\ AB}$	1.55$^{a\ A}$	1.47$^{a\ B}$

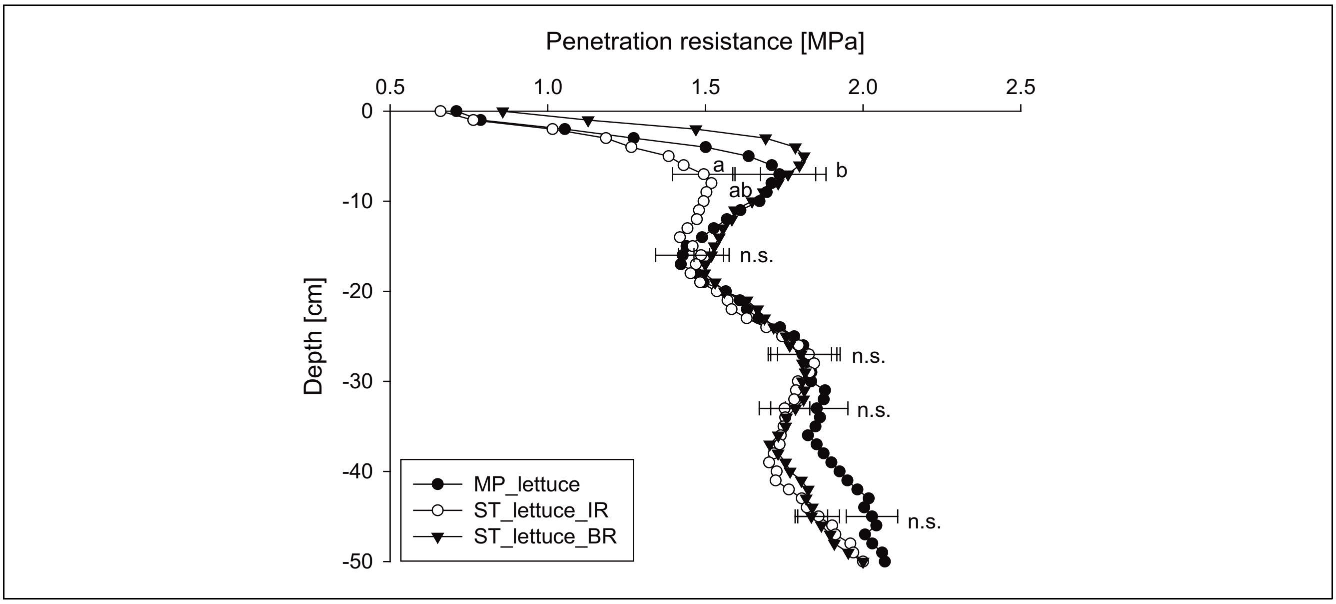

Fig. 3. Penetration resistance under different tillage practices on 15 May 2011. MP_lettuce: moldboard plowing with previous crop lettuce, ST_lettuce_IR: strip-tillage with previous crop lettuce, sampling position in tilled rows, ST_lettuce_BR: strip-tillage with previous crop lettuce, sampling position between planting rows in untilled area. Test of significant differences were performed in 7, 16, 27, 33 and 45 cm soil depth. Data with the same letter are not significantly different, *P* < 0.05; no interactions of treatment and depth were detected. Horizontal bars indicate standard error of means.
Eindringwiderstand bei unterschiedlicher Bodenbearbeitung am 15. Mai 2011. MP_lettuce: Pflug, Vorfrucht Kopfsalat, ST_lettuce_IR: Strip-Tillage, Vorfrucht Kopfsalat, Probenahme in der Pflanzreihe, ST_lettuce_BR: Strip-Tillage, Vorfrucht Kopfsalat, Probenahme zwischen den Pflanzreihen. Mittelwertvergleiche in 7, 16, 27, 33 und 45 cm Tiefe. Gleiche Buchstaben zeigen nicht signifikante Unterschiede, P < 0,05; es bestand keine Wechselwirkung Bodenbearbeitung × Tiefe. Fehlerbalken sind Standardfehler des Mittelwerts.

gravimetric water contents were measured in ST_BR compared to MP at four of the five sampling dates at 0–10 cm.

For the first three sampling dates there were no significant differences in soil water contents between the treatments at 30 cm depth. For the fourth and fifth sampling date, significantly higher gravimetric water content was measured in MP compared to ST_IR. Treatments and sampling position did not differ significantly at 40 cm depth, except on 25 July 2011. In MP, soil water content was significantly higher at 30 cm depth compared to 10 cm and 40 cm with the exception of 25 July 2011. In ST_IR and ST_BR soil water content increased from 10 cm to a depth of 30 cm and decreased from 30 cm to a depth of 40 cm. In deeper soil horizons (10–30 cm and 30–40 cm) differences in gravimetric water content were less noticeable between treatments.

Results of plant available water (Fig. 4) showed significantly lower values in ST_IR compared to MP and ST_BR. MP and ST_BR were not significantly different to each other. Plant available water content ranged between 11.9 L m^{-2} and 43.1 L m^{-2} during the cultivation period. Most consistent plant available water values were detected in ST_BR over the sampling period. Strong variations were measured in MP and ST_IR with differences in plant available water content of 16 L m^{-2} in MP and 18 L m^{-2} in ST_IR.

Tab. 7. Analysis of variance for gravimetric soil water content in white cabbage at 5 sampling dates in June and July 2011 and 2 tillage systems (MP: moldboard plowing, ST: strip-tillage)
Varianztabellen des gravimetrischen Bodenwassergehaltes unter Weißkohl zu 5 Probenahmeterminen im Juni und Juli 2011 bei 2 Bodenbearbeitungsverfahren (MP: Pflug, ST: Strip-Tillage)

Effect	DF	F-value	Pr > F	DF	F-value	Pr > F
		22 June 2011			04 July 2011	
Treatment	2	0.68	0.5407	2	2.31	0.1736
Depth	2	1.93	0.1573	2	85.03	< 0.0001
Treatment × depth	4	4.41	0.0035	4	9.12	< 0.0001
		18 July 2011			25 July 2011	
Treatment	2	3.03	0.1165	2	1.84	0.1769
Depth	2	42.95	< 0.0001	2	6.45	0.0033
Treatment × depth	4	9.88	< 0.0001	4	2.24	0.0753
		02 Aug. 2011				
Treatment	2	7.39	0.0026			
Depth	2	14.62	< 0.0001			
Treatment × depth	4	8.59	< 0.0001			

Tab. 8. Gravimetric soil water content [g g^{-1}] in moldboard plowing and strip-tillage treatments in white cabbage at three different depths and five sampling dates. MP: moldboard plowing, ST_IR: strip-tillage, sampling position in tilled row, ST_BR: strip-tillage, sampling position between rows in untilled area. For each sampling date, data with the same letter are not significantly different; lower case letters refer to individual columns, upper case letters to rows, P < 0.05
Gravimetrische Bodenwassergehalte [g g^{-1}] bei Pflug oder Strip-Tillage unter Weißkohl in 3 Bodenschichten und zu 5 Probenahmeterminen. MP: Pflug, ST_IR: Strip-Tillage, Probenahme in der Pflanzreihe, ST_BR: Strip-Tillage, Probenahme zwischen den Pflanzreihen. Gleiche Buchstaben zeigen nicht signifikante Unterschiede innerhalb jedes Probenahmetermines; Kleinbuchstaben gelten innerhalb der Spalte, Großbuchstaben innerhalb der Zeile, P < 0,05

	Soil depth (cm)			Soil depth (cm)		
	0–10	10–30	30–40	0–10	10–30	30–40
	Gravimetric water content (g·g^{-1})					
		21 June 2011		04 July 2011		
MP	0.20 b C	0.24 a A	0.22 a B	0.18 b C	0.24 a A	0.22 a B
ST_IR	0.23 a A	0.23 a A	0.23 a A	0.21 a C	0.23 a A	0.22 a B
ST_BR	0.22 ab B	0.23 a A	0.23 a AB	0.20 a B	0.23 a A	0.22 a A
		18 July 2011		25 July 2011		
MP	0.20 b C	0.23 a A	0.21 a B	0.22 a B	0.24 a A	0.22 ab AB
ST_IR	0.21 b B	0.22 a A	0.21 a B	0.21 a B	0.22 b A	0.22 a AB
ST_BR	0.22 a AB	0.22 a A	0.21 a B	0.22 a AB	0.22 ab A	0.21 b B
		02 Aug. 2011				
MP	0.17 b C	0.22 a A	0.21 a B			
ST_IR	0.17 b B	0.20 b A	0.20 a A			
ST_BR	0.21 a A	0.20 b A	0.21 a A			

Head weight of lettuce and white cabbage

Head weights for lettuce harvested in spring 2011 did not significantly differ between ST_lettuce (662 g) and MP_lettuce (641 g).

For white cabbage, in 2011 significant differences in average head weight were detected between MP_lettuce (1311 g) and MP (1476 g). There were no significant differences between ST, ST_lettuce and MP (Fig. 5a). In

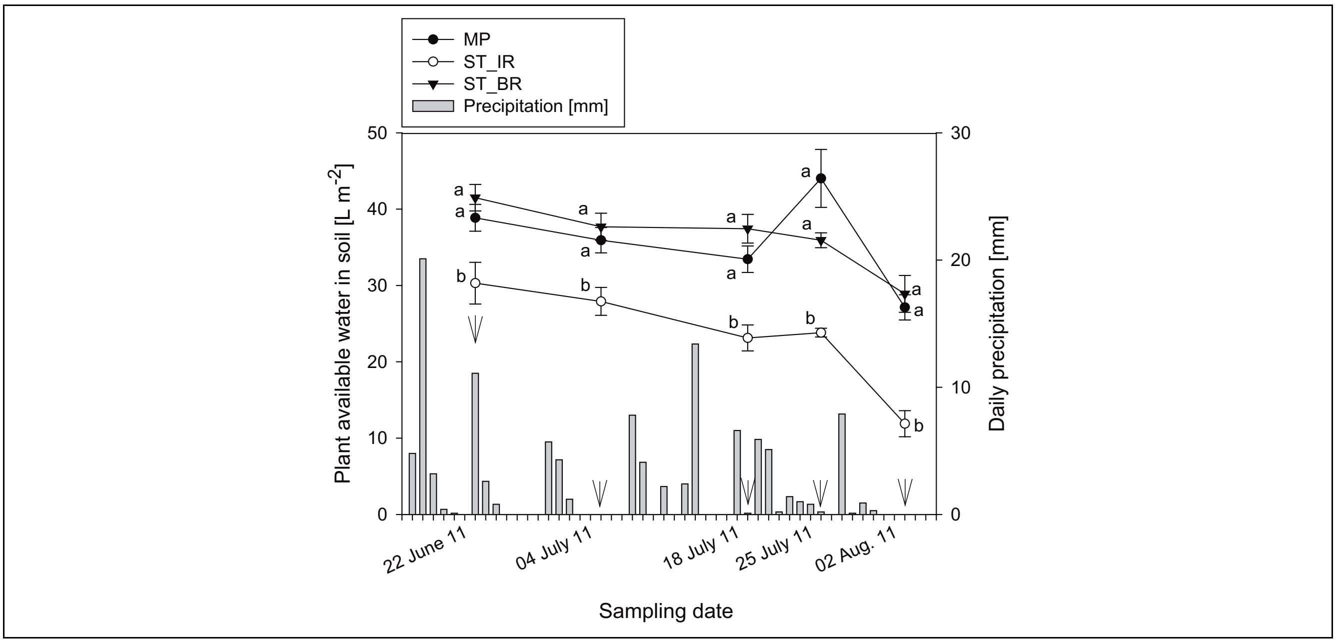

Fig. 4. Plant available water in the soil [L m⁻²] grown with white cabbage and daily precipitation [mm] across 5 sampling dates in June and July 2011. Sampling was conducted down to 40 cm depth. MP: moldboard plowing, ST_IR: strip-tillage, sampling position in tilled rows, ST_BR: strip-tillage, sampling position between rows in untilled area. For individual sampling dates, data with same letter are not significantly different, *P<0.05*. Vertical bars indicate standard error of means.

Pflanzenverfügbares Bodenwasser [L m⁻²] unter Weißkohl sowie tägliche Niederschläge [mm] zu 5 Probenahmeterminen im Juni und Juli 2011. Probenahme bis 40 cm Bodentiefe. MP: Pflug, ST_IR: Strip-Tillage, Probenahme in der Pflanzreihe, ST_BR: Strip-Tillage, Probenahme zwischen den Pflanzreihen. Gleiche Buchstaben zeigen nicht signifikante Unterschiede innerhalb jedes Probenahmetermines, P < 0,05. Fehlerbalken sind Standardfehler des Mittelwerts.

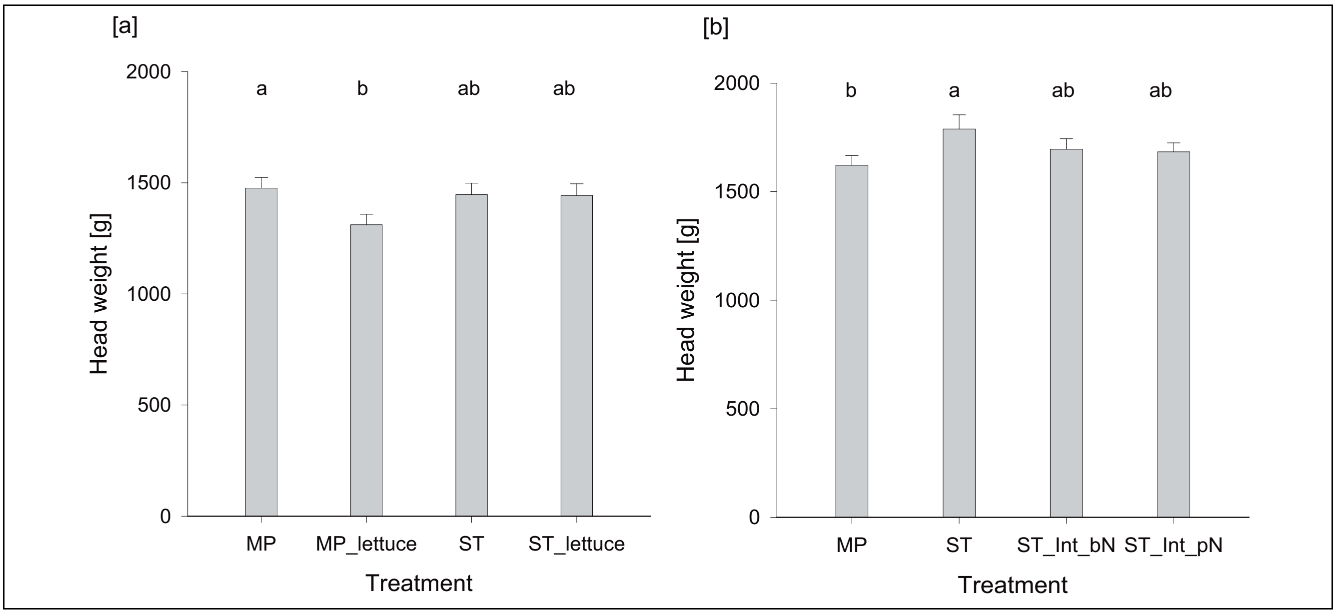

Fig. 5. Average head weight of white cabbage in 2011 [a] and 2012 [b] under different tillage systems, previous crop [a] and fertilizer application systems [b]. MP: moldboard plowing, MP_lettuce: moldboard plowing with previous crop lettuce, ST: strip tillage, ST_lettuce: strip-tillage with previous crop lettuce, ST_Int_bN: intensive strip-tillage with broadcast nitrogen fertilization, ST_Int_pN: intensive strip-tillage with placed nitrogen application. Values with the same letter are not significantly different, *P < 0.05*. Vertical bars indicate standard error of means.

Mittlere Kopfgewichte von Weißkohl 2011 [a] und 2012 [b] in Abhängigkeit vom Bodenbearbeitungsverfahren und Vorfrucht [a] bzw. Düngerausbringung [b]. MP: Pflug, MP_lettuce: Pflug, Vorfrucht Kopfsalat, ST: Strip-Tillage, ST_lettuce: Strip-Tillage, Vorfrucht Kopfsalat, ST_Int_bN: Intensives Strip-Tillage mit breit gestreuter N-Düngung, ST_Int_pN: Intensives Strip-Tillage mit platzierter N-Düngung. Gleiche Buchstaben zeigen nicht signifikante Unterschiede, P < 0,05. Fehlerbalken sind Standardfehler des Mittelwerts.

2012, a significantly lower head weight was detected in MP (1622 g) than in ST (1850 g). Head weight of ST_Int_bN (1723 g) and ST_Int_pN (1684 g) did not differ significantly to MP and ST (Fig. 5b).

Discussion

A comparison of the soil mineral nitrogen results between conservation tillage and conventional tillage systems revealed inconsistent findings. Both lower and higher SMN contents were detected in no-till compared to conventional tillage (Wander and Bollero, 1999; Dalal et al., 2011). However, results from a long-term study in Germany corroborate our findings by reporting that no significant differences in SMN were detected in no-till and conventional tillage treatments over a 10 year period (Gruber et al., 2011).

The artificial rainfall simulation showed a high erosion protective potential of strip-tillage in both the lettuce and white cabbage cultivation.

The amount of soil loss in the current study was similar to investigations of different tillage systems in Saxony (Germany), which were conducted with the same rainfall simulator and the same level of rainfall intensity. In these investigations, cumulative soil losses in sugar beet, barley and winter wheat after 20 minutes of irrigation were up to 270 g m^{-2} in the conventional tillage treatment compared to 100 g m^{-2} in the conservation tillage plots (Nitzsche and Zimmerling, 2004). In general, rainfall simulators have very small working areas. Approximately 50% of the 229 simulators described by Cerdà (1999) have an irrigation area of less than 1.5 m^2. Such simulators are not suitable to reproduce soil erosion processes which are scale dependent, for example overland flow or rill erosion, as they required larger areas (Gómez and Nearing, 2005). To conclude, small scale rainfall simulators are appropriate to establish the effect of soil properties, splash erosion, or the erosion potential of different tillage practices, as in this study with strip-tillage and moldboard plowing. The applied amount of 40 liters per hour reflects a rainfall event which occurs at 20 to 50year intervals (Schmidt et al., 1996).

In general, lower soil erosion risk under conservation tillage compared to conventional tillage was observed in several studies (Blevins and Frye, 1993; Jin et al., 2008; Delaune and Sij, 2012). The key factor of erosion control in conservation tillage systems is the surface covering by straw or mulch (in the current study, 60% of the soil surface was covered), which reduces water velocity and rain drop impact and results in reduced runoff.

Corresponding to the results of the current study, in other investigations higher bulk densities were observed between rows than within rows in strip-tillage treatment with vegetable rotations (Overstreet and Hoyt, 2008). In short-term field experiments, such as the current study, bulk density in conservation tillage systems is often higher compared to conventional tillage (Al-Kaisi et al., 2005; Puget and Lal, 2005). In contrast, in long-term reduced tillage experiments, the bulk density was similar or lower than in conventional tillage fields (Tebrügge and Düring, 1999; Dolan et al., 2006). Lower bulk density is often caused by higher soil organic matter contents because the particle density of soil organic matter is lower than that of mineral soil. Soil organic matter increased in conservation tillage systems, which was due to the crop residues on the soil surface being turned over by micro-organisms into organic matter over time, together with soil particles forming stable aggregates. These factors in conservation tillage systems contribute towards preventing soil losses (Fawcett and Caruana, 2001) and improving water infiltration (Jabro et al., 2011). Evidence of higher water infiltration rates and greater water-holding capacity in this current study helps to explain the later start of soil loss in the strip-tillage plots when compared to the moldboard plowed plots.

Penetration resistance is the main decisive factor controlling root growth and it is a factor for determining the structure and quality of a soil (Tebrügge and Düring, 1999). Similar to the results of bulk density, top soil penetration resistance is higher under conservation tillage than under conventional tillage. This is consistent with most other studies (Vetsch and Randall, 2002; Licht and Al-Kaisi, 2005). In general, penetration resistance increases with depth, whereas the tillage treatment is less influential as depth increases (Erbach et al., 1992). A threshold for critical penetration resistance values for impeded root growth and reduced yields is given between 2.5–3.0 MPa (Taylor and Gardner, 1963). In summary, for our study penetration resistance did not exceed this critical value.

In assuming that strip-tillage between rows (ST_BR) can be compared to no-till, the results of higher moisture content and higher plant available water content between the rows in the current study are consistent with studies which detected higher top soil moisture contents in no-till treatments when compared to conventional treatments (Franzluebbers et al., 1995; Rasmussen, 1999). A possible reason could be a reduced evaporation rate and again an increased infiltration due to the soil being covered with straw residues under conservation tillage techniques (Smika and Unger, 1986; Jones et al., 1994; Licht and Al-Kaisi, 2005).

In the strip-tillage treatment, the low available water content in the tilled zone of ST_IR could be dependent on a variable pore size distribution in the tilled zone. A higher macropore volume was observed by Hussain et al. (1998) in the tilled area within the strip-tillage treatment in the top soil, but these were generally not well connected with subsoil macropores. It might be that in ST_BR, comparable to no-till treatments, the macropores are fewer than in moldboard plowed treatments but they are more homogenously distributed across the top soil and subsoil layers. Consequently, conservation tillage treatments have a larger volume of storage pores that lead to higher water infiltration and plant available water content in no-till treatments compared to conventional tillage treatments (Shukla et al., 2003).

The cabbage yield under strip-tillage of the current study was found to be equal or even higher. This is in contrast to a study examining strip-tillage treatments with different mulches which showed that cabbage yields in strip-tillage treatments were lower than in the conventional tillage treatment using the moldboard plow and disk management (Hoyt, 1999). Decreased yields are often associated with increased weed population, lower soil temperature in spring and no uniform seedbed preparation for guaranteed crop establishment, and in some cases slower nitrogen mineralization (Tiarks, 1977; Triplett Jr. and Dick, 2008). It is possible that the highly modernized techniques and the technical modifications of strip-tillage and the planting equipment used within the present study were responsible for the high yield potential. In another study, sugar beet yield in strip-tillage plots was similar to conventional treatments after 5 years of development and modification of machines and techniques (Evans et al., 2010).

Conclusions

In the light of climate change and the increasing amount of heavy rainfall events predicted for the future, along with the increasing significance of erosion control and soil conservation measures, strip-tillage is showing credible signs of being a suitable tillage practice for field grown vegetables. The erosion control under strip-tillage was highly improved for both vegetables, lettuce and white cabbage. Simultaneously, the head weight was not negatively affected by the strip-tillage system. In 2012, the cabbage head weight was even higher in ST than MP. To integrate such a conservation tillage system into current, practical farming systems for vegetable production, detailed studies examining weeds and further fertilization techniques will additionally be needed. In future, strip-tillage following wheat or other cereals in a multi-year crop rotation including vegetables could be a viable option towards reducing soil loss in erosion-prone crops, such as white cabbage with a simultaneously high yield potential.

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