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# Development of management strategies to control soil erosion in field grown vegetables with a focus on white cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.)

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# List of Abbreviations and Acronyms

| | | | |
|---|---|---|---|
| a.s.l. | above sea level | MgO | magnesium oxide |
| CC | Cross Compliance | MJ | megajoule |
| cm | centimeter | mm | millimeter |
| $cm^3$ | cubic centimeter | MPa | megapascal |
| $CO_2$ | carbon dioxide | N | nitrogen |
| d | index of Agreement | $NH_4$ | ammonium |
| DAP | days after planting | $NO_3$ | nitrate |
| DF | degrees of freedom | NUE | nitrogen use efficiency |
| DSSAT | Decision Support System for Agrotechnology Transfer | P | phosphor |
| DW | dry weight | PET | polyethylene terephthalate |
| e.g. | exempli gratia (for example) | MIXED | mixed linear model |
| Eds | editors | RCBD | randomized complete block design |
| et al. | et alii, and others | RMSE | root mean square error |
| FM | fresh matter | RTK-GPS | Real Time Kinematic-Global Positioning System |
| FW | fresh weight | SMN | soil mineral nitrogen |
| g | gram | t | tons |
| ha | hectare | Wh | working hour |
| $K_2O$ | potassium oxide | yr | year |
| L | liter | °N | degree North |
| LAI | leaf area index | °E | degree East |
| m | meter | °C | degree Celsius |
| $m^2$ | square meter | € | Euro |

# 1 Introduction

## 1.1 Soil erosion -facts and main causes-

Soil erosion is a devastating problem throughout the world. In Europe, approximately 115 million hectares of land, equal to 16% of Europe's total area, are affected by water erosion (SOER, 2010). This amounts to high annual costs caused by both on-site and off-site soil erosion damages, which in the past ranged from 0.7 to 14 billion Euros in Europe (European Commission, 2002). On-site damages are defined as damages, which happen directly on the field in terms of yield losses or soil degradation and off-site damages occur beyond the field, such as pollution of the groundwater or flooded roads. Generally, the tolerable soil loss rate is estimated by less than 1 t ha$^{-1}$ yr$^{-1}$ (Jones et al., 2004). Higher rates have a harmful effect on the soil fertility and soil degradation within a time span of 50 to 100 years. In single storms, soil losses of 20 to 40 t ha$^{-1}$ were measured every two or three years (Van-Camp et al., 2004). The risk of soil erosion depends on both, **environmental and human-caused factors** and erosion effects natural ecosystems, as well as agricultural or forestry systems (Lal, 1990). In general, the **climate** and the **land topography** are the main causes of soil erosion. The duration and intensity of rain determine the amount of soil detachment and subsequent loss from field. The erosive energy of running water therefore depends on the volume and the velocity. Furthermore, the degree of steepness and the slope length affect the erosive potential (Stewart et al., 1990).

Other key factors, which influence soil erosion processes, are **soil properties** and **soil cover**. Soil texture, that means the proportion of clay, silt and sand particles, affects the infiltration and drainage of soils. Generally, sandy soils have a higher water infiltration than clay soils (Ben-Hur et al., 1985). Moreover, the soil particles vary in their ease of detachment. Silt particles, which are small and do not easily form aggregates, are most easily detached (Fullen et al., 1997). The highest risk of soil erosion comes from bare soils, which are exposed to the full erosive power of raindrops and runoff water. Vegetation helps to stabilize soil and control runoff because the erosive energy of raindrops is reduced by the soil cover, and the roots fix the soil particles together. Inadequate land management and particularly intensive agricultural practices are frequently responsible for erosion and soil degradation worldwide. **Deforestation, overgrazing** and **high disturbance tillage** lead to bare land, unstable soil structures, decreasing infiltration rates and finally decreasing soil fertility. Mechanical disturbances by inversion-tillage practices affect soil properties, specifically by disruption of soil aggregation and by burying the crop residues (Tebrügge and Düring, 1999; Figure 1).

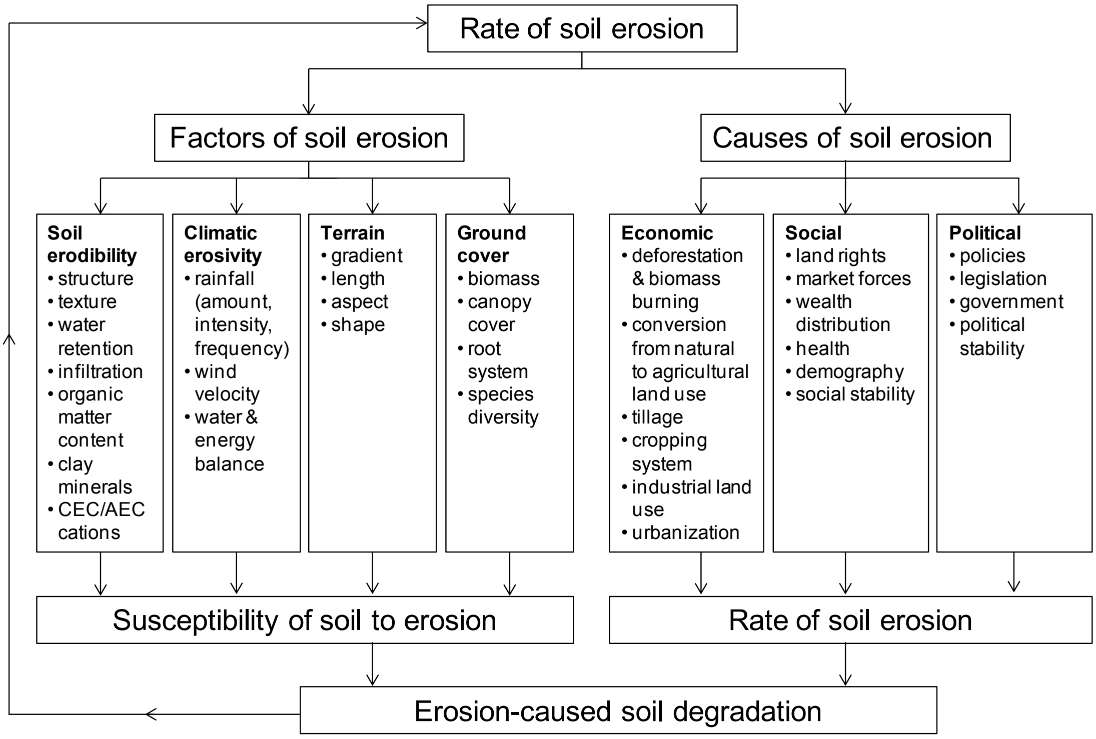

**Figure 1**: Factors and causes of soil erosion and the interaction between them (adopted from Lal, 2001).

## 1.2 Vegetable production in Germany and Europe

The total vegetable production area in Europe reached approximately 4 million ha with a production quantity of 95 million t year$^{-1}$ (FAOSTAT, 2012). Italy and Spain embodies the states with the highest production volumes and account for around 39% of the total harvested vegetables in Europe. The highest production volumes are reached in tomato (*Solanum lycopersicum*) production with 23 million t year$^{-1}$ followed by Brassicas (12 million t year$^{-1}$). In Germany, the total vegetable production area accounts for around 112 000 ha with a total production of 3 million t year$^{-1}$ (Statistisches Bundesamt, 2013). Asparagus (*Asparagus officinalis*) is with 19 000 ha the most important vegetables species, followed by carrots (*Daucus carota* subsp. *sativus*, 10150 ha) and onions (*Allium cepa*, 9500 ha). **White cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.)**, the model plant of this study, is grown on 5840 ha within the German vegetable production area (Statistisches Bundesamt, 2013). The largest cohesive white cabbage production area in Europe is located in the federal state of Schleswig-Holstein in “Dithmarschen” with a production area of 2800 ha. The “Filderebene” in the south of Stuttgart also represents an important and traditional cabbage production region in Germany, which covers an area of 270 ha (Statistisches Bundesamt, 2013). In particular, as it is needed for the production of “Sauerkraut”, white cabbage is gaining worldwide consumer popularity. The production of cabbage and its subsequent processing into Sauerkraut has a considerably long tradition and is highly valued as regional and cultural produce.

## 1.3 Soil erosion in vegetable production

Through the last decades, soil erosion has become more evident in Germany because of (i) an increasing frequency of heavy rainfall events during summer and (ii) a simultaneous increase in terms of land area utilised for erosion-prone spring crops on the fields, such as maize (*Zea mays* L.), sugar beet (*Beta vulgaris* subsp. *vulgaris*) or **field grown vegetables**. These crops are grown with wide row spacing and have a high demand for a finely structured seedbed. The Mediterranean region is even more affected than temperate parts of Europe because of steeper slopes, sparser vegetation, and because rainfall events only occur during specific seasons (Grimm et al., 2002). However, also in the humid European regions, such as in southwest Germany, the on-site and off-site damages caused by soil erosion have increased during the last years, particularly after thunderstorms, where soil was washed onto roads and plantlets were washed away from the fields.

In southwest Germany, which incorporates one of the most important vegetable producing areas known as the “Filderebene” region, a typical vegetable crop rotation includes **lettuce (*Lactuca sativa* L.) – white cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.) – winter wheat (*Triticum aestivum* L.)**, or other small cereals, respectively. Alternative crop rotations can also be **lettuce - lettuce - cover crop (e.g. *Phacelia*) - winter wheat**. Usually, the primary tillage is conducted after cereal harvest in autumn by the mouldboard plough at 20 to 30 cm soil depth (deep inversion tillage). After winter, two passes are performed with a rotary harrow to reduce the weeds and to create optimal seedbed conditions for the following vegetable plantlets. Hence, the soil texture is very finely crumbled and the risk of soil erosion increases with any further soil preparation. For the first lettuce set in spring (March or April), the soil erosion risk is negligible due to lower rainfall intensities and because the soil surface is usually covered by fleece to prevent frost damages. For the second set of vegetables (cabbage or lettuce), which is transplanted in May or June, the erosion risk increases greatly because of additional soil preparation after the lettuce harvest and an increase in heavy rainfall events in June and July. During this time period, the plantlets are still small, the soil surface is uncovered, and the risk of runoff and soil loss is high, in particular on erosion-prone loess soils as they occur on the Filderebene.

## 1.4 Project background and political framework

The need of water erosion control strategies for field grown vegetables is inevitable. Hence, the Baden-Wuerttemberg’s Ministry of Rural Affairs and Consumer Protection (MLR) funded the project “Development of erosion control strategies for field grown vegetables” from 2010 to 2013. The political background of the project was the implementation of the Cross Compliance (CC)-erosion classification in 2010 (ErosionsSchV, 2010). For this regulation, all field parts were divided into soil erosion hazard classes according to the soil erosion risk. Basis for the classification is the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) its revised form, the RUSLE (Renard et al., 1991), and the adapted version for

European soil and environmental conditions, ABAG (Allgemeine Bodenabtragsgleichung; Schwertmann et al., 1987). All equations evaluate the long term average annual soil loss by sheet and rill erosion and are defined by:

$A = R \times K \times L \times S \times C \times P,$

where ***A*** stands for the potential long-term **average annual soil loss** in tons per hectare and year, ***R*** is the **rainfall and runoff factor**, ***K*** is the **erodibility factor** (soil texture is the main factor affecting *K*), ***L*** is the **length-factor** and ***S*** represents the **gradient-factor**. ***C*** stands for the **vegetation and management factor** and ***P*** represents the **support practice factor** (e.g. cross-slope cultivation). The CC-soil erosion hazard classes depend on the **soil type (K-factor)** and the **steepness (slope; S-factor)** of the field parts. There are three classes for water erosion and two for wind erosion (Table 1).

**Table 1:** Soil erosion hazard classes according to the Cross Compliance regulations (modified according to Dölz, 2010).

| Water erosion hazard class | Description | K (soil type) x S (slope) |
|---|---|---|
| $CC_{water0}$ ($CC_{Wa0}$) | Low erosion risk | < 0.3 |
| $CC_{water1}$ ($CC_{Wa1}$) | Erosion risk | 0.3 < 0.55 |
| $CC_{water2}$ ($CC_{Wa2}$) | High erosion risk | ≥ 0.55 |

The time period, during which inversion tillage (e.g. mouldboard ploughing) is permitted, is fixed according to the factor of soil type and steepness. On fields prone to erosion ($CC_{Wa1}$), the use of mouldboard plough is only permitted if the following crop is sown before 1 December and immediately after the harvest of the previous crop. In all other cases, moldboard ploughing is prohibited during winter (from 1 December to 15 February). For field areas, which are classified in $CC_{Wa2}$, mouldboard ploughing is prohibited for row crops with a row distance of more than 45 cm. For all other crops moldboard ploughing is prohibited over winter. The use of mouldboard plough from 16 February to 30 November is only allowed, if the sowing or planting follows immediately after soil tillage (ErosionsSchV, 2010).

In the state of Baden-Wuerttemberg, 16% of all field parts are categorized as $CC_{Wa1}$ and 7% as $CC_{Wa2}$ (LUBW, 2010). Independently of the CC-erosion classification, the state Soil Protection Act (LBodSchAG, 2004) and the Federal Soil Protection Act (BBodSchG, 1998) remain valid for all field parts.

For vegetables growers, who have fields prone to erosion or for those who are in a legal conflict concerning the CC-regulation, there is urgent need to develop strategies which allow for cultivating fields in accordance to the political requirements to minimize soil erosion and to achieve high yields.

## 1.5 Strategies of erosion control in field crops

Several erosion control strategies are already in use in crop production, for example growing cover crops, contour tillage, wind and water barriers e.g. hedgerows, trees, grassed waterways or conservation tillage (reduced tillage).

In general, any **soil cover** can reduce water runoff and soil loss. **Cover crops** cover the soil surface by aboveground biomass, which protects the soil from being detached (Langdale, 1983; Hartwig, 1988). Another erosion control measure is the **contour ploughing** or **the cross-slope cultivation,** which is widely-spread in the US. This is a tillage practice where the direction of tillage runs across the slope, and often uses contour lines. Water breaks are created, which reduces gully and rill erosion. **Wind and water barriers**, such as hedgerows or trees slow down the velocity of wind and water, and reduce the slope length.

The most important and common strategy to control soil erosion is convincingly known as conservation tillage (Lal 1998; Erenstein 2003). Several **conservation tillage practices** are known and established for many field crops, such as maize, sugar beet or potatoes. By definition a tillage practice is classified as conservation tillage, if more than 30% of the soil surface is covered by residues (Baker et al., 2002). Soil inversion tillage by mouldboard plough is replaced by non-inversion tillage practices and even no-tillage (zero tillage) is possible.

**Reduced tillage options** are widely used particularly for sugar beets or cereals production, with the main objective to prevent soil erosion and avoid soil degradation. The soil is tilled by chisel plough to prepare the soil before sowing. As the soil is not inverted, crop residues from the previous crop cover soil surface as a mulch layer and provide a protection against soil erosion. Any tillage leads to faster soil warming in spring, faster nitrogen mineralization and better weed and pest control compared to **no-tillage** (Mäder and Berner, 2012). However, the most useful practice to prevent soil erosion is no-tillage, without any soil disturbance (Kay et al., 2009; Prasuhn, 2012). The high protection capacity against soil erosion stems from the mulch layer from the previous crop at the soil surface, which results in higher infiltration rates, increased water storage, and lower evaporation compared to conventional, inversion-tillage practices by a mouldboard plough (Ball et al., 1997a; Hatfield et al.; 2001, Govaerts et al., 2009). Nevertheless, alongside the benefits eventuating from no-tillage, there may also be disadvantages. For temperate climate zones, yield potential tends to be lower under no-till because of a lower seedbed temperature in spring. This often results in delayed crop emergence and lower emergence rates (Kaspar et al., 1990; Dwyer et al., 1995; Johnson and Hoyt, 1999). Additionally, adoption of no-till results in changes in weed infestation and crop diseases which (i) often reduce yields and (ii) possibly require higher application rates with increased costs of pesticides (Ball and Davies, 1997b; Anken et al., 2004,). To combine the benefits of conservation tillage (soil conservation) with the advantages of conventional, inversion tillage (high yield potential), **strip-tillage** could be a promising tillage practice. This practice has attracted interest during the last decades, especially for maize production in the US (Vyn and Raimbault, 1993).

Strip-tillage can be considered as a conservation technique, where the straw and mulch residues from the previous crop remain on the soil surface and the latter seeding or planting rows are tilled exclusively in autumn and/or in spring by a strip-tiller. Several studies have shown high benefits of strip-tillage for maize and sugar beet concerning erosion control, soil quality, water storage and yield (Al-Kaisi and Kwaw-Mensah, 2007; Overstreet, 2009; Nash et al., 2013). Strip-tillage can lead to higher infiltration rates, higher soil moisture content, and a lower evaporation rate compared to conventional tillage (Al-Kaisi and Hanna, 2002). Higher soil temperatures within the tilled strips are valuable assets of strip-tillage compared to no-tillage because of a lower risk of delayed seed germination and plant emergence (Licht and Al-Kaisi, 2005; Celik et al., 2013). Strip-tillage also has economic benefits because of synergies of combining operations (e.g., seedbed preparation, seeding and fertilization) in one pass, and thus results in lower fuel and labour requirements compared to conventional tillage (Crosson et al., 1986).

## 1.6 Strategies of erosion control in field grown vegetables

The project "Development of erosion control strategies for field grown vegetables" used two approaches to develop, test and improve strategies to control soil erosion. The first approach was the use of **row covers**, and the second was the adoption and improvement of the **strip-tillage** system for field grown vegetables.

Row covers belong to the group of agrotextiles, cover the soil and reduce the impact of the rainfall energy which minimizes the risk of soil erosion. Two frequently used row covers are **insect netting**, which is used in organic agriculture for pest control, and **fleece or non-woven fabrics**, which serve as frost protection in spring and accelerate plant growth (Rekika et al., 2009; Olle and Bender, 2010) However, there are unresolved issues regarding the microclimate under the covers and the influence on crop growth. The air temperature and relative humidity increases significantly especially under fleece (Mermier et al. 1995; Gimenez et al., 2002), which can result in better growing conditions on the one hand, but also in a higher risk of plant diseases on the other hand (Jenni et al., 2003).

For vegetable production, conservation tillage practices such as **strip-tillage** are not widely utilized. Vegetable seedlings are dependent on a fine crumbled seedbed, which is hardly achieved by no-tillage. Due to the less promising results attainted in vegetable experiments with conservation tillage practices, there are currently no adequate technical solutions on the market (Phatak et al., 2002; Price and Norsworthy, 2013). Nonetheless, due to existing knowledge and the success of strip-tillage in maize and sugar beet, it appears plausible to adapt and improve strip-tillage for field grown vegetables. Some studies have shown that strip-tillage is possible for tomato (*Solanum lycopersicum* L.), sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) and cucumber (*Cucumis sativus*; Hummel et al., 2002; Luna J., 2003; Overstreet et al., 2010). However, many challenges still remain regarding suitable planting, fertilization, herbicide management and the integration of the system in a vegetable crop rotation.

Strip-tillage for vegetable production offers several options with different tillage intensities and fertilizer applications. The general procedure for a temperate, climate with field grown vegetables can be considered as follow:

1) **Stubble tillage (optional)** after cereal harvest is recommended, particularly if harvest residues are not homogeneously distributed.
2) **Weed control** by a non-selective herbicide around 10 days before the tillage operation is conducted.
3) **First strip preparation in autumn:** On heavy soils (> 10% clay), the strips should be prepared in autumn to expose the soil to frost over winter. On sandy soils, it is possible to till the strips in spring. For vegetables, such as cabbage, the strips are 20 cm deep and 20 cm wide. For high strip quality and to guarantee an exact transplanting process, it is important to use a RTK-GPS (Real Time Kinematic-Global Positioning System) guidance system for strip preparing with a precision of ± 2.5 cm.
4) **Weed control in spring** by second use of a non-selective herbicide around 10 days before transplanting.
5) **Second, shallower strip preparation (optional)** in spring can be conducted shortly before transplanting. It is especially recommended if the soil structure in the tilled area is not sufficiently fine-structured for vegetable transplants. It can be combined with a band-placed, fertilizer application through the coulters of the strip-tiller.
6) **Transplanting** of vegetable plantlets with a total-controlled planting machine. The second, band-placed fertilizer application can be conducted during the transplanting process through the coulters (optional). Saved tracks of the RTK-GPS guidance system from the strip-tillage process are used, to make sure that the transplants are placed in the tilled area.

Step 1) and step 5) can be omitted for a **standard, non-intensive strip-tillage**. In this case, the fertilizer application has to be undertaken via broadcast. For an **intensive strip-tillage,** all steps are included with the option of **band-placed nitrogen fertilization** during the second tillage pass and during transplanting in spring (Figure 2). Based on these working steps, in the current study, different strip-tillage intensities and different fertilizer application techniques were investigated, tested and adapted to specific requirements of white cabbage.

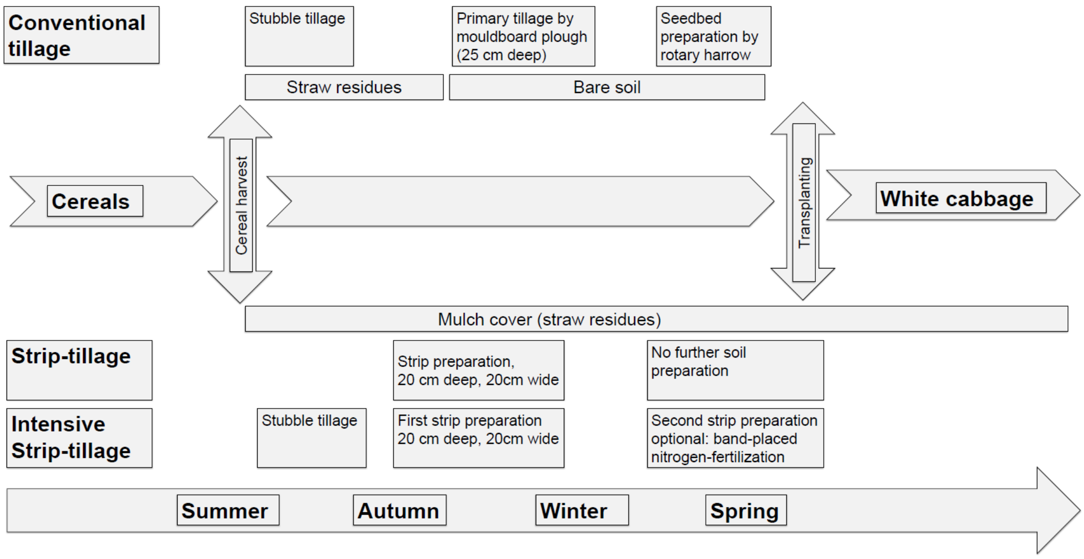

**Figure 2**: Working steps of different strip-tillage treatments and conventional tillage for white cabbage production on a clay loam, as tested in the current study.

## 1.7 Cabbage growth simulation

For the purpose of meeting the consumer demands of white cabbage in Germany and Europe, it is important to understand growth processes, as well as nutrient and water demand. The fact that field experiments are laborious, costly and time consuming, make **process-oriented crop growth simulation models** a valuable tool for simulating crop growth, predicting yield potentials and adapting management systems (Boote et al., 1996; Jagtap and Abamu, 2003). Several crop growth simulation models are commonly used and accepted worldwide (Hoogenboom et al., 2003; Keating et al., 2003; Van Ittersum et al., 2003). The **CROPGRO** model embedded in the **Decision Support System for Agrotechnology Transfer (DSSAT**; Jones et al., 2003), was initially developed for legume crops (Wilkerson et al., 1983; Boote et al., 1987; Hoogenboom et al., 1994). Based on climatic, soil and environmental conditions, CROPGRO is able to simulate a vast number of different scenarios, such as the crop response to different fertilizers or the effect of irrigation management strategies (Boote et al., 1998). Due to the generic nature of CROPGRO it was possible to integrate other crops including bell pepper (*Capsicum annuum* L.), cabbage (*Brassica oleracea* L.), tomato (*Lycopersicon esculentum* Mill.), sweet corn (*Zea mays* L.) and green bean (*Phaseolus vulgaris* L.) in the model. The CROPGRO cabbage model was initially calibrated under tropical, Hawaiian climate conditions (Hoogenboom et al., 2003). To date, there is no calibration and validation of the CROPGRO cabbage model for white cabbage cultivars under temperate, European climate conditions.

## 1.8 Objectives

The overall aim of the current study was to investigate, develop and adapt strategies to control soil erosion in field grown vegetable production. This is done, in accordance with the political framework, and with keeping in view the importance of high yield potentials and high practicability for farmers. The key focus is placed on the use of row covers (agrotextiles: fleece and nets) and the development and adaption of strip-tillage for vegetables, with white cabbage incorporated as the model crop. Finally, a process-oriented crop growth simulation model (DSSAT CROPGRO) is calibrated and evaluated for a standard cabbage cultivar under temperate, European climate to describe, understand and improve cabbage growing.

The specific objectives were to

(1) assess the effect of row covers (fleece and nets) on soil erosion and the possible side effects on cabbage growth,

(2) adapt and improve the strip-tillage system for field grown vegetables,

(3) investigate the effect of strip-tillage on soil loss, water regime and selected soil properties,

(4) investigate the effect of strip-tillage on nitrogen dynamics in soil and plants, and to

(5) calibrate and evaluate the DSSAT CROPGRO cabbage model for white cabbage production under temperate, European climate conditions.

Field experiments were conducted from 2011 to 2013 at the experimental stations ‘Hohenheim Gardens’ and ‘Ihinger Hof’ of the University of Hohenheim. The results are presented in four scientific articles, which form the body of the present thesis. **Publication I** deals with the influence of row covers on soil erosion and plant development in cabbage cultivation and the possible side effects because of modified microclimate under the row covers. Results of a two-year field experiment are presented. In **publication II** and **publication III,** the development, adaption and the testing of the strip-tillage system for field grown vegetables (white cabbage and lettuce) from three experimental years is described. Here, **publication II** presents the results of strip-tillage on selected soil properties (erosion control, bulk density, penetration resistance and soil moisture contents). **Publication III** focuses on nitrogen availability under strip-tillage. A key issue addressed is the effect on soil mineral nitrogen, nitrogen availability and nitrogen uptake of cabbage plants in terms of different nitrogen application techniques (broadcast and band-placed) and different tillage intensities. The overall goal of the strip-tillage experiments was to achieve a similar yield potential compared to conventional tillage. **Publication IV** presents results from the evaluation of the plant growth simulation model DSSAT CROPGRO for a standard white cabbage cultivar grown within a temperate climate zone.

# 2 Publications

The present thesis consists of four articles which have been published in peer-reviewed journals. These four articles constitute the body of this thesis. Further publications in non peer-reviewed journals or presentations from national and international conferences (i.e.,posters or oral presentations) are presented in the Appendix (Table A6). For citation of the four articles, please use the references given below.

**Publication I:**

Übelhör A., Gruber S., Schlayer M. and Claupein W. (2014): Influence of row covers on soil loss and plant growth in white cabbage cultivation. Plant, Soil and Environment Volume 60, No. 9, pp. 407-412

**Publication II:**

Übelhör A., Witte I., Billen N., Gruber S., Hermann W., Morhard J. and Claupein W. (2014): Feasibility of strip-tillage for field grown vegetables. Journal für Kulturpflanzen – Journal of Cultivated plants Volume 60 (11), pp. 365-377.
DOI: 10.5073/JfK.2014.11.01

**Publication III:**

Übelhör A., Gruber S. and Claupein W. (2014): Influence of tillage intensity and nitrogen placement on nitrogen uptake and yield in strip-tilled white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*). Soil & Tillage Research, Volume 144, pp. 156-163.
DOI: 10.1016/j.still.2014.07.015

**Publication IV:**

Übelhör A., Munz S., Graeff-Hönninger S. and Claupein W. (2014): Evaluation of the CROPGRO model for white cabbage production under temperate European climate conditions. Scientia Horticulturae, Volume 182, pp. 110-118.
DOI: 10.1016/j.scienta.2014.11.019

# 3 Influence of row covers on soil loss and plant growth in white cabbage cultivation

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**Publication I:**

**Übelhör A., Gruber S., Schlayer M. and Claupein W. (2014): Influence of row covers on soil loss and plant growth in white cabbage cultivation. Plant, Soil, and Environment, Volume 60, No. 9, pp. 407-412**

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*Based on the prediction of increasing frequency of heavy rainfall events resulting in a higher soil erosion risk, farmers have an urgent need for strategies to control soil erosion. Especially in vegetable production systems, such as white cabbage, the soil erosion risk is high due to intensive tillage practices, wide row distances and late soil covering by leaves. Row covers, such as fleece or insect nets, are better known as frost protection or in organic farming as a protection against insects and birds. But row covers could also serve as a tool for erosion control in vegetable cultivation. The following article deals with the investigation and the evaluation of row covers as an erosion control strategy concerning soil loss and water runoff, and the influence of the modified microclimate under fleece and net covers on white cabbage growth.*

*Plant Soil Environ.* *Vol. 60, 2014, No. 9: 407–412*

# Influence of row covers on soil loss and plant growth in white cabbage cultivation

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## ABSTRACT

Row covers are usually used to protect plants from insects and cold temperatures, and to accelerate plant growth. But they could also serve as an erosion control strategy. For this reason, fleece (FC) and net covers (NC) in white cabbage (*Brassica oleracea* convar. *capitata* (L.) Alef. var. *capitata* L. f. *alba*) cultivation were tested in a two-year field experiment to determine effects on soil erosion, plant growth and plant diseases. Soil loss under FC was reduced on average by 76% and under NC by 48% compared to the non-covered control treatment (CO). Soil temperature did not differ significantly in either of the experimental years between the treatments and ranged from 17.2–18.2°C in 2012 and from 18.7–18.9°C in 2013. Soil moisture content, air temperature and relative humidity were always highest under FC, followed by NC and CO. Leaf area index was also highest under FC across all sampling dates. The fresh matter head yield under FC and NC was significantly higher (80 t/ha) compared to CO (66 t/ha) in 2012. An opposite result was detected in 2013, with the highest yield in CO (64 t/ha) and lowest under FC (53 t/ha). Overall, for moderate climate conditions, the row covers seem to be beneficial as a suitable erosion control strategy.

**Keywords**: microclimate; soil erosion; agrotextiles; vegetables; artificial rainfall experiment

Soil erosion is a devastating problem throughout the world. The tolerable rate of soil losses by wind or water erosion in Europe is estimated to be less than 1.0 t/ha/year (Jones et al. 2004). Cumulative mean soil erosion rates in tilled agriculture in Europe are between 4.5 and 38.8 t/ha/year. In Europe, 115 Mio. ha of land are at high risk of water erosion and 42 Mio. ha of wind erosion (European Environment Agency 1998). In vegetable production systems, the tillage intensity is often high, with at least one pass by the mouldboard plough in autumn and two passes in spring by rotary harrow. The consequences are bare fields with unstable, finely structured soils accompanied by a very high risk of soil erosion and soil degradation. Conservation tillage (non-inversion tillage, no-tillage) can reduce the erosion, because of a mulch layer, which prevents the soil against the high energy of raindrops or against wind (Lal 2000). For vegetable production, especially for transplants, there are up to now only very few technical solutions for conservation tillage such as reduced tillage or no-tillage. Furthermore vegetable transplants are dependent on a finely crumbled seedbed for optimal growth conditions, which can hardly be achieved by non-inversion or no-till. All in all, the high erosion risk, due to wide row distances (> 45 cm) and late soil covering by the plants requires an erosion control strategy. The use of row covers (agrotextiles, direct covers, crop covers) could be used to prevent water erosion. Non-woven fabrics (e.g. fleece) are fielded for frost protection in spring and to accelerate plant growth. Insect netting or mesh cover are normally used in organic agriculture to protect crops against insect pests (Rekika et al. 2009, Olle and Bender 2010). However, the agrotextiles can be used as an erosion control measure, because the erosive energy of raindrops is reduced if the soil is covered by row covers (Davies et al. 2006).

In Central Europe, white cabbage (*Brassica oleracea* convar. *capitata* (L.) Alef. var. *capitata* L. f. *alba*) is usually transplanted in April or May. The soil covering by leaves does not occur before the end of June or beginning of July. During these months, the frequency of heavy rainfall events is particularly high accompanied with a high soil erosion risk. At the same time, June and July are the warmest months in the year, so the microclimate under row covers can be modified, resulting in higher air and soil temperatures, higher relative humidity, and lower irradiance compared to open-air conditions in non-covered plots (Mermier et al. 1995, Gimenez et al. 2002). When row covers are used as erosion control measures, in contrast to the original use as frost protection and against insect pests, the covering is over an extended period and over a latter part of the year. The effect on the plant development of white cabbage under row covers in summer is not yet known, so the objectives of the study were to determine the erosion protective potential of different covers in white cabbage and to investigate the microclimate and its influence on plant growth, yield and on plant diseases.

## MATERIAL AND METHODS

To determine the soil erosion protective potential of the different row covers in July 2012 and rainfall simulation (RS) was conducted three times at the research station belonging to the University of Hohenheim, 'Hohenheim Gardens' (48°42'42''N, 9°11'57''E). The artificial rainfall was generated by an irrigation system with a rainfall intensity of 25 mm/h and a Christiansen's coefficient of uniformity of 94% (Christiansen 1942). There were six bare plots with two different slopes (12% and 18%) and a plot size of 3 m × 1 m. One plot per slope was covered by insect netting with a mesh diameter of 1.35 mm × 1.35 mm (Rantai K; NC), the other one with a polypropylene, 17 g-density, non-woven fabric (fleece; FC) and the third treatment was the non-covered control (CO). The soil type was a stagnogleyic Cambisol and the soil texture was a clay loam (CL; FAO 2006). The soil-water suspension was collected at the end of the plot in collecting boxes. After the simulation (rainfall duration: 2 h) the suspension was filtered and the amount of water was measured. The soil filtrate was weighed, dried at 105°C until a constant weight was achieved, and re-weighed.

The field experiment (FE) was carried out in 2012 and 2013 on the experimental station belonging to the University of Hohenheim at Ihinger Hof in Southwest Germany (48°44'40''N, 8°55'26''E). The average temperature was 9.3°C in 2012 and 8.7°C in 2013. The rainfall in 2012 was 728 mm and in 2013 it was 922 mm. The 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 (deeper 20 cm) represented loam (L; FAO 2006). White cabbage cv. Kalorama was transplanted (14/5/12 and 15/5/13; row distance: 50 cm) in a randomized complete block design with 3 treatments and 3 replicates with a plot size of 20 m × 2 m. Soil preparation was done by a mouldboard plough in autumn 2011 and 2012, and by a rotary harrow one day before transplanting in spring. The treatments were, similar to the RS experiment, fleece cover, net cover and non-covered control. Fertilizer application to a target value of 270 kg N/ha (ENTEC Perfect, 15% N + 2% P + 17% K), weed and pest control were done according to the best management practice in all treatments.

Soil temperature and soil moisture were determined by a soil thermometer (testo 925, Test AG, Lenzkirch, Germany) and a TDR probe (TRIME-FM, IMKO, Micromodultechnik, Ettlingen, Germany) once a week in the year 2012. In 2013, permanent sensors were installed in all plots to record air temperature (Tinytag Plus 2, Gemini Data Loggers, West Sussex, UK), relative humidity of the air (Tinytag Plus 2, Gemini Data Loggers, West Sussex, UK), soil moisture (DECAGON Echo-5, Dacagon Devices, Pullman, USA) and soil temperature (Thermistor, 6507B/30, Unidata Europe (Starlog), Neustadt, Germany) under FC, NC and CO from transplanting up to removing the covers.

Plant samples were taken in 2012 and 2013 in all plots biweekly until the direct covers were removed (2012: 99 days after transplanting (DAP); 2013: 63 DAP). Three (2012), or five (2013) plants per plot were harvested to determine leaf area index (LAI; was measured 3 times; LI-3100 Area Meter; LI-COR, Lincoln, USA) and dry weight (DW) per plant by drying the samples at 60°C.

For determination of pests and diseases, a visual rating of cabbage plants was conducted on the day of the cover removal in both years. Every single cabbage plant was verified, according to symptoms of frequently occurred cabbage diseases. Infected plants were counted and plant samples were taken for microscopic analysis of the pathogen.

At harvest time (2012: 138 DAP, 2013: 148 DAP) 15 plants per plot were harvested by cutting off the aboveground biomass. This was done in order to determine the fresh matter (FM) yield of the whole plant and the FM head yield as a measure of the marketable yield. Harvest index was calculated by division of the head weight by the total aboveground biomass per plant.

Statistical analyses were conducted with SAS (SAS/Stat 2009). The statistical significance of differences in mean values of LAI, DW per plant, FM yield and harvest index were analyzed with the SAS procedure Proc Mixed, whereby treatment and replicates were given as fixed effects and the sampling position and plot were given as random effects. Different sampling dates were analyzed independent of each other. For letter description a multiple *t*-test was used only after finding significant differences via an *F*-test.

## RESULTS AND DISCUSSION

**Artificial rainfall experiment**. In total, the soil loss of the 12% slopes was about 78% lower under FC than under CO. For NC, the soil loss was about 29% higher than CO. For the 18% slopes, the soil loss under FC was reduced by 90% and under NC by 78% (data not shown). The runoff ranged between 0.56 L (FC) and 0.86 L for the 12% slopes and between 1.63 L (CO) and 1.73 L (FC) for the 18% slopes (Table 1). Similar results were observed at RS with geotextiles (cotton fibers) also with very low soil loss in plots which were covered with textiles. In contrast to the recent study, the runoff was higher under the covers compared to the non-covered plots (Giménez-Morera et al. 2010). Other studies showed that the infiltration rate is higher and the total soil loss by inter-rill erosion is reduced (Smets et al. 2007) when the soil is covered with straw mulch or agrotextiles. This is reasoned by the restriction of movement by splash, which slows the flow velocity and decreases the runoff-volume (Lattanzi et al. 1974, McGregor et al. 1988).

**Microclimate measurements**. In the FE in 2012, the soil temperature at a depth of 10 cm was on average 1°C higher under FC and 0.5°C higher under NC compared to CO (17.2°C). The soil moisture was highest under FC (27%) followed by NC (26%) and CO (25%; data not shown).

In 2013, the soil temperatures did not significantly differ between the treatments. The soil temperatures ranged between 18.7°C and 18.9°C during the growing period (Figure 1a). These results are contrasting to the study of Wells and Loy (1985), where soil temperatures were highest under row covers. The soil moisture was highest under FC (24%), followed by NC (22%) and CO (21%; Figure 1b). The average daily air temperature, which was measured under the covers, amounted to 20°C under FC, 18°C under NC and 17°C in CO (Figure 1c). The maximum temperature reached 45°C under FC, followed by 37°C under NC and 32°C in CO. Minimum temperature was 7°C under FC and 2°C under NC and CO. High air temperature under row covers was also found in a study in Spain, in Chinese cabbage (*Brassica rapa* L. subsp. *pekinensis* (Lour.) Hanelt) cultivation, with higher air temperature found at the beginning of the cultivation period under FC compared to the non-covered treatment. However, this difference disappeared throughout the growing period (Gimenez et al. 2002). In contrast, in our study, the higher temperature under FC lasted throughout the entire growing period. The average relative humidity varied over time in the recent study in covered plots between 78.4% (NC) and 82.0% (FC; 77.9%). Under CO the relative humidity reached 77.9%. These results are similar to a study by Mermier et al. (1995), who detected higher relative humidity under non-woven fabrics in lettuce cultivation.

Table 1. Total soil loss and runoff after three sequences of artificial rainfall (25 mm/h) on 2 slopes with 3 treatments of soil cover in July 2012

| | Slope (%) | | | |
|---|---|---|---|---|
| | 12 | 18 | 12 | 18 |
| | soil loss (g DW) | | runoff (L) | |
| Net cover | 3.93 | 2.73 | 0.71 | 1.67 |
| Fleece cover | 0.68 | 0.95 | 0.56 | 1.73 |
| Control | 3.04 | 9.67 | 0.86 | 1.63 |

DW – dry weight

**Leaf area index**. At all sampling dates and in both years, LAI was always highest under FC. The LAI ranged in 2012 from 0.03 (CO and NC) on 25th May to 3.87 (FC) on 9th July and in 2013 between 0.27 (CO) and 2.72 during growing season (FC; Table 2). Gimenez et al. (2002) also detected higher LAI under row covers for Chinese cabbage at the beginning of the cultivation period.

**Yield**. During the growing period until the covers were removed, there were always higher DW yields under NC and FC compared to CO (Figure 2a) in 2012.

The DW per plant reached on average from 9 g/plant, 34 DAP to 101 g/plant, 62 DAP.

Average FM head yield under NC and FC was about 80 t/ha, but a significantly lower yield was detected under CO (65 t/ha). The results corroborate with data from garlic (Rekowska and

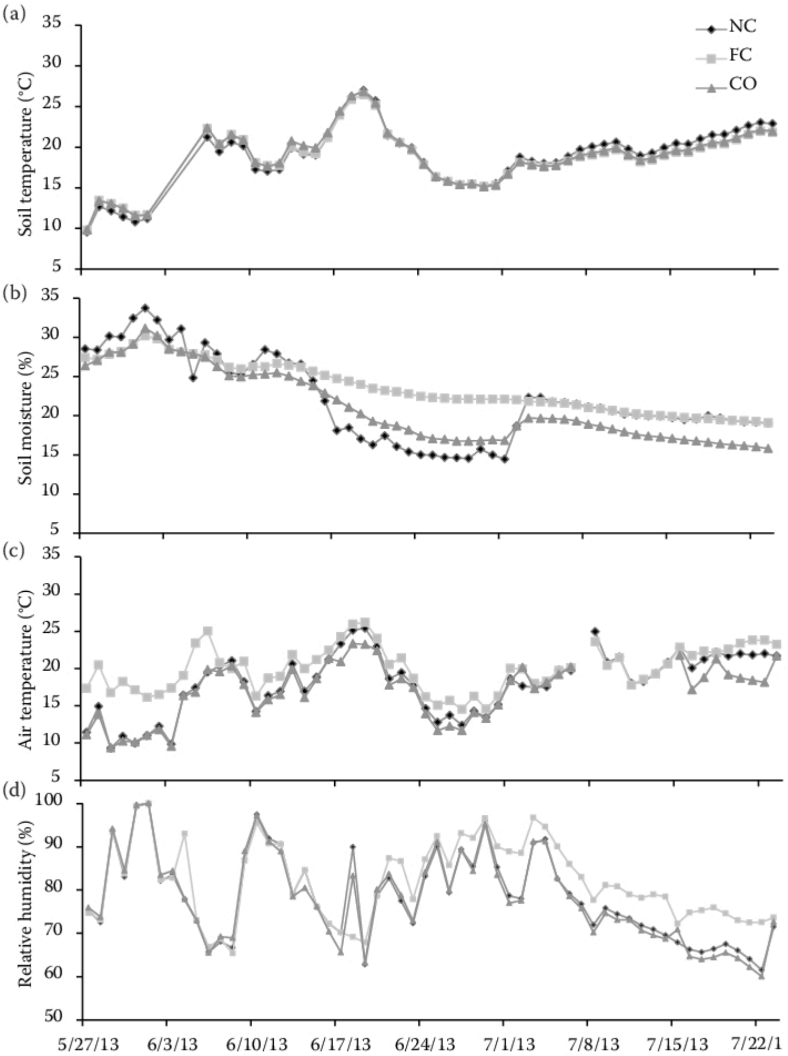

Figure 1. Daily average of soil temperature (a); soil moisture (b); air temperature (c), and relative humidity of air (d) under net cover (NC), fleece cover (FC) and control (CO)

Skupień 2007), shallot (Tendaj and Mysiak 2006), cucumber (Ibarra-Jiménez et al. 2004) and lettuce (Rekika et al. 2009), which were also reported to have higher yields under row covers.

The situation was different in the second experimental year 2013 when cabbage yield (FM) was highest under CO (64 t/ha) and lowest under FC (53 t/ha, Figure 3a). This result was contrasting to most other studies; however, results exist in Chinese cabbage, spinach, beet and lettuce, where the yield was not significantly affected by the row covers (Peacock 1991, Gimenez et al. 2002). The aboveground fresh matter

Table 2. Leaf area index of cabbage leaves in 2012 and 2013

| Treatment | 2012 | | | 2013 | | |
|---|---|---|---|---|---|---|
| | 25.05. | 22.06. | 09.07. | 18.06. | 02.07. | 18.07. |
| Net cover | 0.03$^a$ | 1.48$^a$ | 3.48$^a$ | 0.29$^a$ | 1.25$^b$ | 1.95$^b$ |
| Fleece cover | 0.04$^a$ | 1.49$^a$ | 3.87$^a$ | 0.42$^a$ | 1.70$^a$ | 2.72$^a$ |
| Control | 0.03$^a$ | 0.84$^b$ | 2.72$^a$ | 0.27$^a$ | 1.24$^b$ | 2.09$^b$ |

No significant differences for values with the same letters in column $P < 0.05$

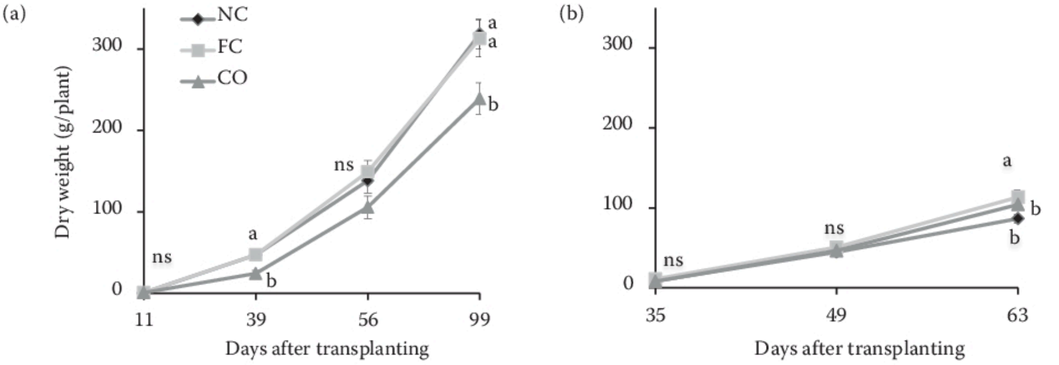

Figure 2. Dry weight of cabbage plants from the different sampling dates in 2012 (a) and 2013 (b). No significant differences for values with the same letters $P < 0.05$. NC – net cover; FC – fleece cover; CO – control

biomass was not significantly different between the treatments in both years (Figure 3b).

The harvest index corresponded to the fresh matter yield. Significantly higher harvest index was recorded under FC (0.58) and NC (0.55) compared to CO (0.48) in 2012. In the second experimental year, a significantly higher harvest index was measured under CO (0.60), compared to the FC (0.54; Figure 4). This indicates that the partitioning (ratio between head and the complete aboveground biomass) of the cabbage plants was not affected by the row covers.

**Diseases and pests**. Row covers by net and fleece can be a physical barrier against cabbage maggot (*Delia radicum* L.) in radish (Rekika et al. 2008) and cauliflower (Millar and Isman 1988) and against flea beetle (*Phyllotreta cruciferae*) in Chinese cabbage (Andersen et al. 2006). In the current study, the infestation with flea beetle in CO (data not shown) might have been the reason for the low yield in 2012. An infestation by cabbage rot (*Sclerotinia sclerotiorum*) occurred under FC where 4% of the cabbage heads were infested compared to 0.5% of the cabbage heads under NC with no infection under CO. No symptoms of *Sclerotinia* rot were visible in 2013. A slightly higher risk of plant diseases under row covers seems to be possible, as also documented for lettuce with a higher infection rate of rib discoloration and tip-burn in lettuce plants under fleece cover (Jenni et al. 2003).

In conclusion, based on this study's findings, the tested row covers seem to be suitable for the control of soil erosion. Also the environmental conditions under the row covers are favored for plant growth; fleece and net can have an additional beneficial effect, regarding higher LAI and similar or higher biomass production under FC and NC. In temperate climate zones, such as Central Europe, and in the case of timely removal of the covers, the risk of plant diseases is predictable.

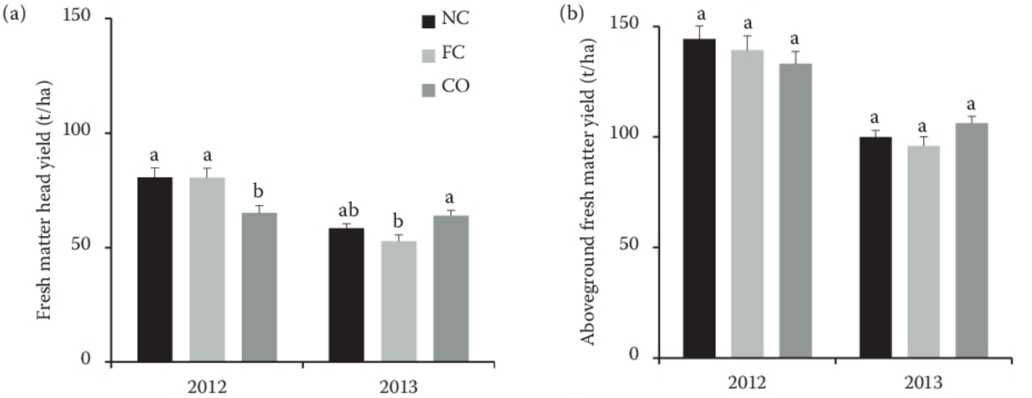

Figure 3. (a) Fresh matter (FM) cabbage head yield and (b) aboveground FM yield in 2012 and 2013. No significant differences for values with the same letters $P < 0.05$. NC – net cover; FC – fleece cover; CO – control

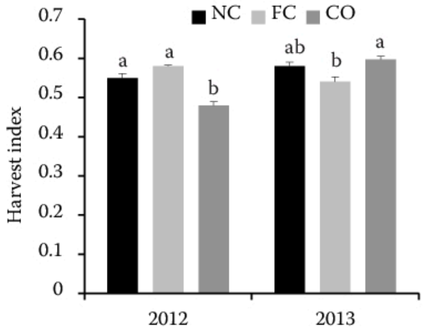

Figure 4. Harvest index of white cabbage in 2012 and 2013. No significant differences for values with the same letters $P < 0.05$. NC – net cover; FC – fleece cover; CO – control

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# 4 Feasibility of strip-tillage for field grown vegetables

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*Conservation tillage is a sustainable and long-term erosion control strategy. For field crops, such as maize or sugar beet, conservation tillage has been widely accepted by farmers for a long time mainly under dry climates. However, for field grown vegetables, such as lettuce or cabbage, there is a lack of technical solutions to adopt conservation tillage. Based on the steadily increasing risk of soil erosion and the resulting legal requirements of the European Union within the Federal Soil Protection Act and the Cross Compliance regulations, it is inevitable to develop and to modify existing conservation tillage practices for the specific requirements of field grown vegetables. Strip-tillage, which combines the advantages of conventional, inversion tillage practice with those of no-tillage, could be a promising way to control soil erosion with simultaneously high yield potential for field grown vegetables. The following article presents preliminary results from field experiments of strip-tillage in lettuce and white cabbage cultivation.*

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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-

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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

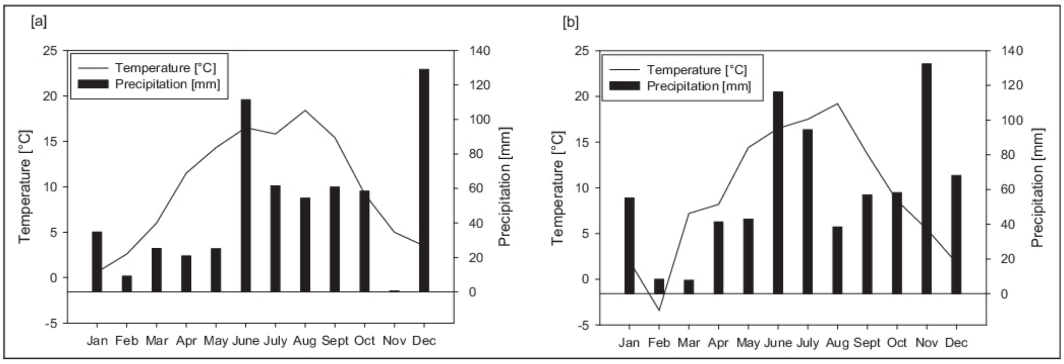

**Fig. 1.** **Monthly average temperature and precipitation in 2011 [a] and 2012 [b] at Ihinger Hof**
*Monatliche mittlere Temperaturen und Niederschläge 2011 [a] und 2012 [b] am Ihinger Hof*

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 FI-Astar™ 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 m², 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 m²) 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 m² 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:

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

### *Soil characteristics and crop yield*

For determination of bulk density five 100 cm³ 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

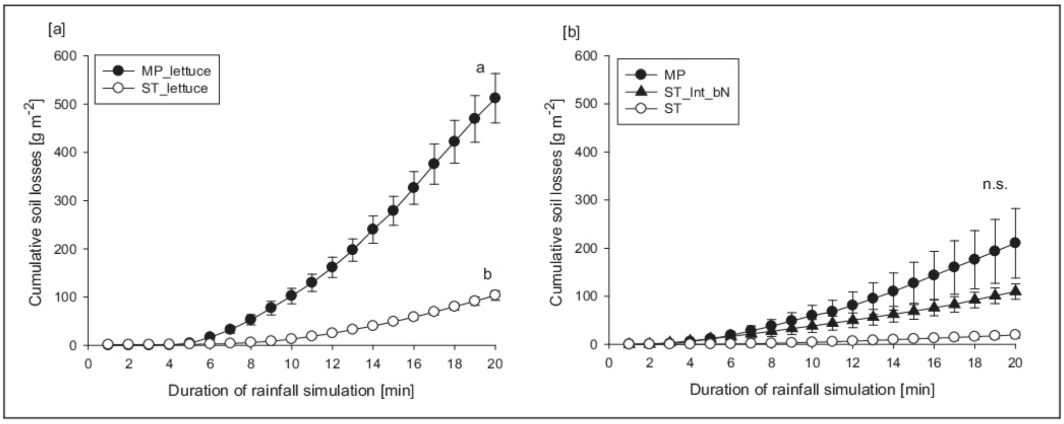

**Fig. 2.** Cumulative soil loss [g m$^{-2}$] during 20 min of simulated rainfall (2 L min$^{-1}$) in [a] 2011 and [b] 2012. MP_lettuce: moldboard plowing with lettuce as previous crop, ST_lettuce: strip-tillage with lettuce as previous crop, MP: moldboard plowing, ST: strip-tillage, ST_Int_bN: intensive 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, $P < 0{,}05$*

| | 10 cm | 30 cm | 40 cm |
|---|---|---|---|
| | | Bulk density (g cm$^{-3}$) | |
| Treatment_position | | | |
| 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 | $1.53^{a\ AB}$ | $1.55^{a\ A}$ | $1.47^{a\ B}$ |

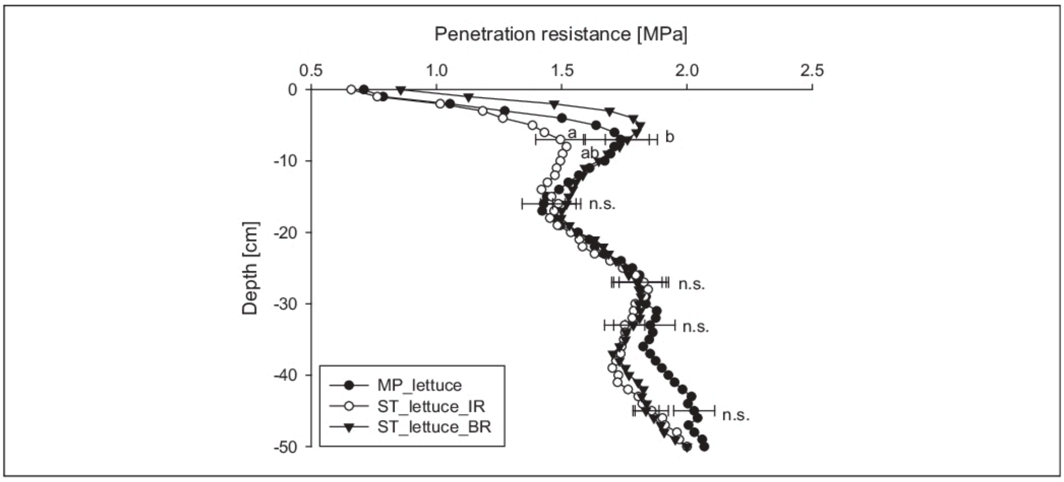

**Fig. 3.** **Penetration resistance under different tillage practices on 15 May 2011. MP_lettuce: moldboard plowing with previous crop lettuce, ST_lettuce_IR: strip-tillage with previous crop lettuce, sampling position in tilled rows, ST_lettuce_BR: strip-tillage with previous crop lettuce, sampling 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

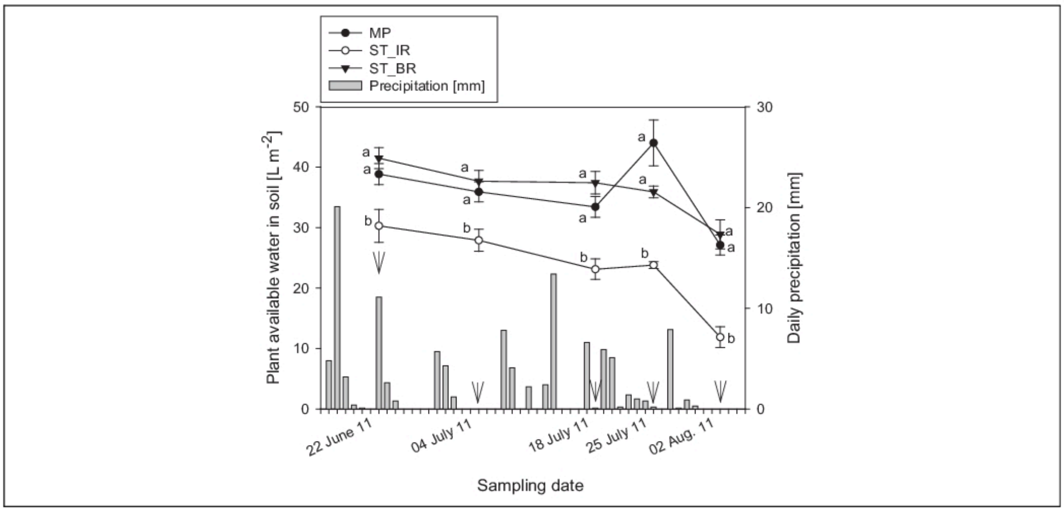

**Fig. 4.** **Plant available water in the soil [L m$^{-2}$] grown with white cabbage and daily precipitation [mm] across 5 sampling dates in June and July 2011. Sampling was conducted down to 40 cm depth. MP: moldboard plowing, ST_IR: strip-tillage, sampling position in tilled rows, ST_BR: strip-tillage, 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.*

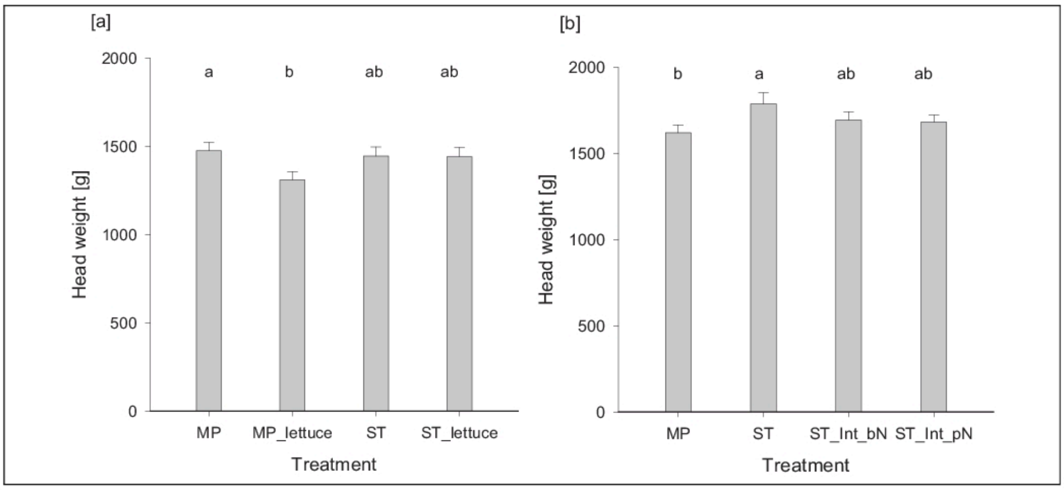

**Fig. 5.** **Average head weight of white cabbage in 2011 [a] and 2012 [b] under different tillage systems, previous crop [a] and fertilizer application systems [b]. MP: moldboard plowing, MP_lettuce: moldboard plowing with previous crop lettuce, ST: strip tillage, ST_lettuce: strip-tillage with previous 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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# 5 Influence of tillage intensity and nitrogen placement on nitrogen uptake and yield in strip-tilled white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*)

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**Übelhör A., Gruber S. and Claupein W. (2014): Influence of tillage intensity and nitrogen placement on nitrogen uptake and yield in strip-tilled white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*). Soil & Tillage Research, Volume 144, pp. 156-163. DOI: 10.1016/j.still.2014.07.015**

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*The results, presented in publication II, showed significantly lower soil loss and favorable water regime under strip-tillage compared to conventional tillage, including utilization of the mouldboard plough, in lettuce and white cabbage cultivation. Furthermore, results after two experimental years indicate a high yield potential under strip-tillage. Beside the confirmation of the high yield potential, the focus in the second strip-tillage article was on the nitrogen availability under strip-tillage in terms of different tillage intensities and different nitrogen fertilizer application techniques. For this research approach, nitrogen status, under single (strip preparation in autumn) and double (strip preparation in autumn and spring) strip-tillage, as well as band-placed and broadcast nitrogen fertilization, were investigated in soil and plants during the whole cabbage growing period.*

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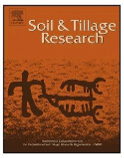

# Influence of tillage intensity and nitrogen placement on nitrogen uptake and yield in strip-tilled white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*)

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Fertilizer placement

ABSTRACT

Field grown vegetables with wide row spacing would likely benefit from the conservation tillage practice, strip-tillage, with regards to minimizing soil erosion or increasing soil moisture contents, but there are only few studies for strip-tilled vegetables at present. For this reason, a 2-year field experiment was performed in South West Germany to investigate the effect of strip-tillage under broadcast and placed nitrogen application on nitrogen availability and yield of white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*). The treatments were fall strip-tillage (ST), intensive strip-tillage with tillage both in fall and spring (STi; all of them with broadcast nitrogen fertilization) and intensive strip-tillage with band-placed nitrogen (STi_pN). In 2013, a fifth treatment was added, which was ST additional sowing of *Phacelia* (*Phacelia tannacetifolia*) as a cover crop (ST_Phac). A conventional tillage treatment (MP; moldboard plowing) was used as the control. No significant differences in soil mineral nitrogen (SMN) were detected in spring (20 ± 5 kg N ha$^{-1}$) and at harvest time (5 ± 0.9 kg N ha$^{-1}$) between the MP and all strip-tillage treatments from 0–90 cm soil depth, except for significantly lower SMN contents in ST_Phac in spring 2013 (5 kg N ha$^{-1}$). During the growing period, the SMN contents in strip-tillage treatments tended to be higher than in the MP control. Results of nitrogen content in plants, N-uptake, and nitrogen use efficiency (NUE) showed higher values under ST compared to the more intensive strip-tillage treatments (STi and STi_pN). The cabbage yield ranged between 65 t ha$^{-1}$ (MP) and 74 t ha$^{-1}$ (ST) in 2012 and 50 t ha$^{-1}$ (STi_pN) and 58 t ha$^{-1}$ (MP) in 2013. The fall strip-tillage treatment (ST) seems to be as effective as the conventional moldboard plowing for white cabbage in terms of N availability and yield. These results could be used to apply or improve strip-till systems with respect to other similar vegetables, which are (i) exposed to high erosion risk because of the wide row spaces and (ii) which are dependent on high N demand for adequate growth.

## 1. Introduction

Conservation tillage, especially no-till, is the most effective way to reduce soil erosion and nitrate leaching, and to increase soil organic matter and water contents in soil (Triplett Jr. and Dick, 2008). In poorly drained soils, however, it is a great challenge to achieve similar yields to that of conventional tillage systems, when comparing yields to a no-till system. Reasons for a lower yield potential can be due to poor seedbed conditions, slower plant development, and impeded root growth under non-inversion tillage practices (Licht and Al-Kaisi, 2005). Furthermore, lower soil temperature, higher soil moisture, and slower mineralization under no-tillage can result in delayed early crop growth and finally lower yields (Alvarez et al., 1998). To avoid these negative effects, strip-tillage could be a viable option towards combining the benefits from no-till practices, such as erosion control, together with some of the advantages from conventional tillage practices with regards to the moldboard plow. Strip-tillage is a non-inversion tillage practice; it disturbs the row, but retains the inter-row space as untilled with all residues from the previous crop covering the soil (Vyn and Raimbault, 1993). Thus, less than one third of the total field area is tilled, and two-thirds of the area remains undisturbed. Particularly for maize (*Zea mays* L.), sugar beet (*Beta vulgaris*), and soybean (*Glycine max* L.), strip-tillage was tested successfully (Al-Kaisi and Kwaw-Mensah, 2007; Randall and Vetsch, 2008; Evans et al., 2010). For field grown vegetables, only few studies exist (Hoyt, 1999; Overstreet and Hoyt, 2008) although especially for vegetables the erosion risk is very high because of the

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high tillage intensity, large row spacing, and late soil covering by plants. Field grown vegetables, such as white cabbage (*Brassica oleracea* convar. *capitata* var. *alba*), have a high nutrient demand and a need of finely crumbled soil. The common way to produce high yielding white cabbage is to till the soil once by the moldboard plow, and then at least twice by a rotary harrow or a rotary cultivator to provide optimal conditions for planting and establishment of the young plants. No-tillage would seldom meet these requirements. Therefore, on the one hand, strip-tillage could be a solution to minimize the risk of soil erosion in vegetable production, and, on the other hand, help to maintain a high yield level. There is, however, still concern as to whether mineralization of nutrients in the soil would take place adequately, and whether the cabbage plants are able to take up the nutrients from the solid, untilled area in strip-till with high bulk density and potentially with poor root penetration (Kubota and Williams, 1967; Kay and Vandenbygaart, 2002).

Additionally, in the non-tilled zones, it is not possible to incorporate fertilizers so that broadcast fertilizer remains on the soil surface for a while after their application (Malhi et al., 1996). No incorporation consequences could then result in high volatilization losses (Mengel, 1982) and increased immobilization of nutrients if crop litter, containing a high C/N ratio, would then remain on the surface of the soil (Malhi et al., 2001). Hence, one approach to minimize the volatilization and to simultaneously increase N-uptake and nitrogen use efficiency (NUE) involves the utilization of fertilizer placement techniques (Malhi and Nyborg, 1990). Deep band fertilizing is frequently used in conservation tillage and consists of a band of fertilizer that is applied at a depth of 5–15 cm below the soil surface (Rehm, 1999). Nitrogen placement fertilization at 5–15 cm soil depths can produce greater root mass than with having N-fertilization at 0 cm depth or than from a broadcast fertilization only reaching the soil surface (Murphy and Zaurov, 1994).

For field grown vegetables, there have been no known investigations regarding the effects of a strip-tillage system combined with a band-placed nitrogen fertilization approach. For this reason, a 2-year field experiment with white cabbage was conducted to test the hypotheses that nitrogen uptake is less efficient in broadcast application than in band-placed application and, in combination with more frequently tilled strips (tillage in fall and spring), results in higher mineralization, better seedbed conditions, and finally in higher crop yields compared to strip-till treatment with less intense soil preparation (only fall preparation).

To prove these hypotheses following issues need to be clarified:

(1) What is the effect of strip-tillage and N-fertilization practices on the soil mineral nitrogen content and is there an improved nitrogen use efficiency by band-placed nitrogen fertilization compared to the broadcast application?
(2) What effect has two times strip-till and the fertilizer placement on plant establishment, N-uptake and yield of white cabbage?
(3) Is it possible to achieve a similar yield potential under strip-tillage than under conventional tillage?

## 2. Material and methods

### 2.1. Site and experimental design

The field experiment was performed in Southwest Germany at the experimental station Ihinger Hof of University of Hohenheim (48°44′N, 8°55′E) during 2011/2012 and 2012/2013. The average annual rainfall of the location is 690 mm, and the average annual temperature is 8.1 °C. The soil type of the fields was predominantly a stagnogleyic Cambisol, and the texture of the upper layer (0–20 cm) was a clay loam (CL), and the second layer (>20 cm) represented a silty clay (SiC) (FAO, 2006). The fields had a mean slope of 8% in south–north direction. In both experimental years, the experimental design was a randomized complete block design with four replicates with 6 m × 20 m per plot. In 2011/2012, four treatments were established, and in 2012/2013 a fifth treatment was added (Table 1). Treatment 1 was conventional tillage by a moldboard plow and rotary harrow (MP), treatments 2–5 were performed as strip-tillage. In treatment 2, strips were prepared only one time in fall, and cabbage was transplanted in spring without any further tillage (ST). A broadcast nitrogen fertilization was conducted. Treatments 3 and 4 had increased tillage intensity with strip preparation in fall and a shallow loosening of the strips by the strip-tiller in spring before transplanting. Additionally, stubble tillage was performed by a harrow after harvest of the previous crop winter triticale (cv. Talentro). In treatment 3, nitrogen was applied by broadcasting (STi) whereas in treatment 4 a band-placed nitrogen fertilization was conducted (STi_pN). In 2012/2013, treatment 5 was added, which was similar to ST, but *Phacelia* (*Phacelia tannacetifolia*) was sown as a cover crop after cereal harvest in 2012 (ST_*Phac*). The first tillage operation in ST, STi, STi_pN, and ST_*Phac* was done by a RTK-GPS based strip-tiller (Horsch 'Focus') on September 29th (2011) and on October 25th (2012). The strips were 20 cm deep and 20 cm wide. The second shallow loosening in STi and STi_pN was performed by the same strip-tiller on April 30th (2012) and May 14th (2013). White cabbage cv. Marcello (*Brassica oleracea* convar. *capitata* var. *alba)* was transplanted on 1st May (2012) and May 15th (2013), with 50 cm row distance in row and between row by a modified total-controlled transplanter (Checchi & Magli) with RTK-GPS guidance system for an exact transplanting.

### 2.2. Fertilization and plant protection

The crop requirement for potassium, phosphorous, and magnesium fertilization was determined according to IGZ fertilizer recommendations (Feller et al., 2011) by soil sampling in spring. An amount of 94 kg $\mathrm{K_2O}$ ha$^{-1}$ and 45 kg MgO ha$^{-1}$ was broadcast in

**Table 1**
Treatments and tillage operations for the experimental years 2011/2012 and 2012/2013.

| Treatment | Tillage operation | N-fertilization | Year |
|---|---|---|---|
| Moldboard plowing(MP) | Moldboard plowing<br>Rotary harrowing | Broadcast | 2011/2012<br>2012/2013 |
| Strip-tillage (ST) | Strip-tillage | Broadcast | 2011/2012 2012/2013 |
| Intensive strip-tillage, broadcast nitrogen fertilization(STi) | Strip-tillage in fall<br>Strip-tillage in spring | Broadcast | 2011/2012<br>2012/2013 |
| Intensive strip-tillage, band placed nitrogen fertilization(STi_pN) | Strip-tillage in fall<br>Strip-tillage in spring | Band placed | 2011/2012 2012/2013 |
| Strip-tillage, with *Phacelia* as cover crop in 2012(ST_*Phac*) | Strip-tillage in fall | Broadcast | 2012/2013 |

spring 2012 and 188 kg $K_2O$ ha$^{-1}$ in spring 2013. There was no need to apply P in both years, and no Mg was applied in 2013 either.

Soil samples were taken from 0 cm to 90 cm depth in all plots to determine the soil mineral nitrogen (SMN) content ($NH_4^+ - N + NO_3^- - N$) in spring before transplanting. The SMN content was subtracted from the mineral nitrogen target value of 270 kg N ha$^{-1}$ for fertilization of white cabbage, and the difference was applied by ENTEC 26 (7.5% $NO_3^- - N$ and 18.5% $NH_4^+ - N$). The N fertilizer was broadcast in a single dose in MP, ST, STi, and ST_Phac in the day of transplanting. For STi_pN, the fertilizer was split in a first application during the tillage operation in spring across the tines of the strip-tillage machine, and a second dose was applied during the transplanting of white cabbage. Here, the fertilizer was placed directly into the tilled planting row by tubes which were installed at the special mulch blades on the planting machine. The space between the planting rows remained unfertilized.

For weed control, glyphosate (3 l ha$^{-1}$) was applied in both experimental years in fall before preparing the strips and in spring before the second loosening and transplanting. All other weed, pest, and disease control were done according to best management practices.

### 2.3. Data collection

For the monitoring of soil mineral nitrogen (SMN) content during the growing seasons, soil samples were collected in each plot at a depth of 0–30 cm by a core sampler on regular dates, namely 14, 28, 43, and 56 days after planting (dap), in 2012 and 13, 27, 41, and 55 dap in 2013. After the harvest of white cabbage, soil samples were taken from 0 cm to 90 cm depth. In all four strip-tillage treatments (ST, STi, STi_pN, and ST_Phac), soil sampling was conducted both within the tilled planting row (IR) and in the non-tilled area between the planting row (BR). The soil samples were dried for 24 h at 105 °C, and after grinding the soil, the SMN ($NH_4^+ - N + NO_3^- - N$) was analyzed by flow injection analysis according to the standards from VDLUFA (International Organization for Standardization, 1996) with a nitrogen analyzer FIAstar™ 5000 (Tecator, Foss, Rellingen, Germany).

Plant samples were taken for determination of the plant N content together with the soil samples at the same days, in both experimental years. Three plants per plot were harvested, one from the upper third of the slope, one from the middle, and one from the bottom third of slope. The whole cabbage plant inclusive of the root was dug out with a spade to a depth of 30 cm. The plant roots were washed above a sieve with a mesh diameter of 0.6 mm, and roots were separated from the shoot. Roots and aboveground biomass were dried at 60 °C to determine dry matter yields. Nitrogen contents in plants were analyzed with a macro elemental analyzer Vario MAX CNS (Elementar, Hanau, Germany), according to the Dumas method.

For calculation of N-uptake in the aboveground biomass, the nitrogen content (%) in cabbage plants was converted into kg N ha$^{-1}$ and multiplied with the dry matter yield of cabbage plants:

$$\mathrm{N-uptake(kg\ N\ ha^{-1}) = dry\ matter\ yield(kg\ ha^{-1})} \times \frac{\%\mathrm{N}}{100} \qquad (1)$$

For yield determination, three transects were chosen (hill slope, foot slope, and back slope) per plot, and six consecutive plants per transect were harvested, totaling 18 plants per plot. The total plant biomass was determined first, and then the cover leaves were removed and the cabbage heads were weighed. One-eighth of cabbage head and five cover leaves were shredded and dried at 60 °C, afterwards the dry matter was determined, and the nitrogen concentration was subsequently measured.

The nitrogen use efficiency of harvest date is defined as the ratio of dry matter yield to N supply and was calculated according to

$$\mathrm{NUE\ (kg\ dry\ matter\ yield\ kg^{-1}\ N)} = \frac{\mathrm{Dry\ matter\ yield\ (kg\ ha^{-1})}}{\mathrm{N_{supply}\ (kg\ \ N\ ha^{-1})}} \qquad (2)$$

where dry matter yield was the yield of total dry matter of aboveground biomass at harvest, and $N_{supply}$ was the available nitrogen in soil at spring (SMN + N fertilized).

For the calculation of nitrogen budget, the N-uptake at harvest (kg N ha$^{-1}$) was subtracted from the N-supply (270 kg N ha$^{-1}$) at spring.

### 2.4. Statistical analysis

For the analysis of variance, the SAS procedure MIXED was used (SAS/STAT, 2009). The experimental design in 2012 and 2013 was a randomized complete block design (RCBD) with three tillage treatments (T), two fertilization techniques (N) and three sampling positions (Pos) for each plot (P) with four replications (R). The model in syntax from Patterson (1997) is given by:

$$\mathrm{T + T\ (N) + R :\qquad P + Pos}$$

where fixed effects are given before the colon, random effects are given after the colon and interactions by a dot between the corresponding main effects. In 2013 *Phacelia*, as the cover crop was added as an additional factor as previous crop [PC] in the model.

Different soil and plant sampling dates were analyzed separate from each other. For letter description, a multiple *t*-test was used only after finding significant differences as results of the *F*-test.

## 3. Results

### 3.1. Soil mineral nitrogen

Before fertilization in spring and at harvest in 2012, the treatments did not significantly differ in SMN at depths of 0–90 cm. The values ranged from 17–25 kg N ha$^{-1}$ in spring and 3–4 kg N ha$^{-1}$ at harvest (Fig. 1a). Before fertilization in spring 2013, significantly lower SMN contents were detected from samples from 0–90 cm in ST_Phac (5 kg N ha$^{-1}$) compared to all other treatments; this effect was no longer visible at harvest time when SMN contents were about 5 kg N ha$^{-1}$ in all treatments (Fig. 1b).

The SMN contents at 0–30 cm soil depth decreased in 2012 from fertilization time until harvest in all treatments except MP for IR sampling with increased SMN at the beginning of the cabbage's growing period. The decrease of SMN during the season occurred in both the non-tilled area (BR) between the plant rows and in the tilled area of the strips (IR). The level of SMN in the rows was between 84 kg N ha$^{-1}$ (MP) and 183 kg N ha$^{-1}$ (STi_pN) early after planting and 15 kg N ha$^{-1}$ (ST) and 41 kg N ha$^{-1}$ (STi_pN) 56 dap (Fig. 2a); there were similar values between rows (BR), with a trend towards to lowest SMN in STi_pN, and the highest in ST (Fig. 2b).

There was no consistent trend for the treatments in SMN contents over the entire growing period in 2013. Highest SMN values were detected over the sampling period, similar to 2012, in STi_pN for IR sampling with about 200 kg N ha$^{-1}$ 13 dap (Fig. 2c). For BR, the SMN contents varied between about 20 and 140 kg N ha$^{-1}$ during the growing period (Fig. 2d). All in all, SMN contents under MP never exceeded the SMN contents of all other treatments.

### 3.2. Aboveground biomass and biomass of roots

Aboveground biomass (dry weight per plant) was highest in ST during the growing season in both years, with significant differences to all other treatments for aboveground biomass in 2012 at

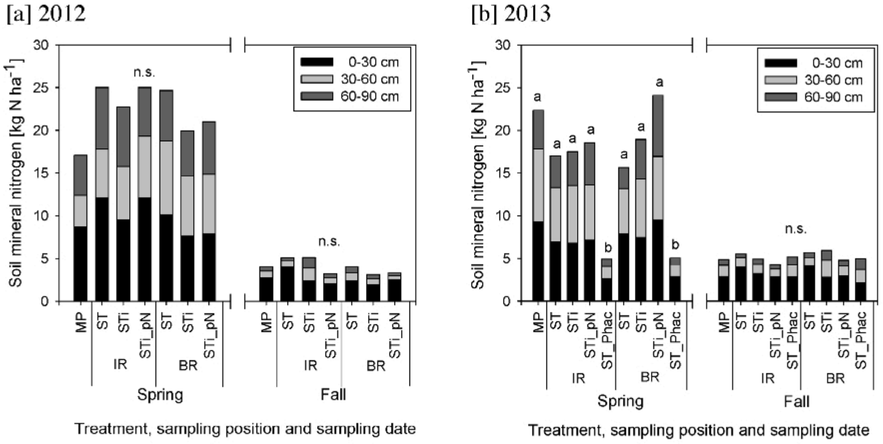

**Fig. 1.** Soil mineral nitrogen content from 0 cm to a depth of 90 cm in spring and fall of 2012 [a] and 2013 [b] under different tillage treatments and different sampling positions. IR: soil samples were taken in the tilled row; BR: soil samples were taken from the untilled area, between the row. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; STi_pN: intensive strip-tillage with band-placed nitrogen fertilization; ST_Phac: strip-tillage with *Phacelia* as cover crop. No significant differences for values with same letters, $P < 0.05$, n.s.: no significant differences; each sampling date was analyzed separate from each other.

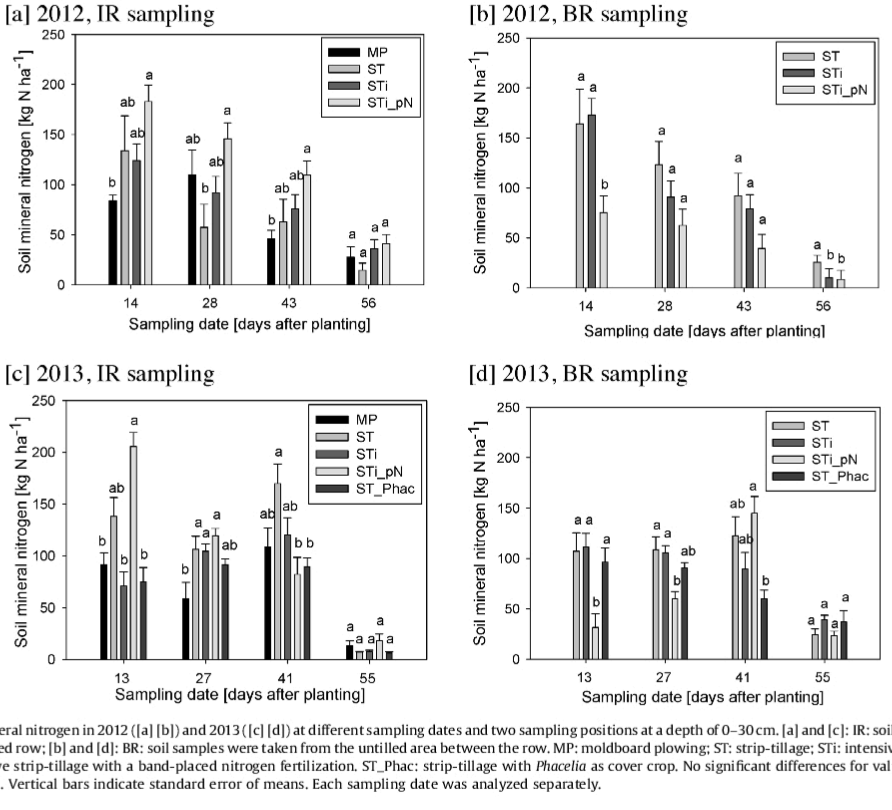

**Fig. 2.** Soil mineral nitrogen in 2012 ([a] [b]) and 2013 ([c] [d]) at different sampling dates and two sampling positions at a depth of 0–30 cm. [a] and [c]: IR: soil samples were taken in the tilled row; [b] and [d]: BR: soil samples were taken from the untilled area between the row. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; ST_pN: intensive strip-tillage with a band-placed nitrogen fertilization. ST_Phac: strip-tillage with *Phacelia* as cover crop. No significant differences for values with same letters, $P < 0.05$. Vertical bars indicate standard error of means. Each sampling date was analyzed separately.

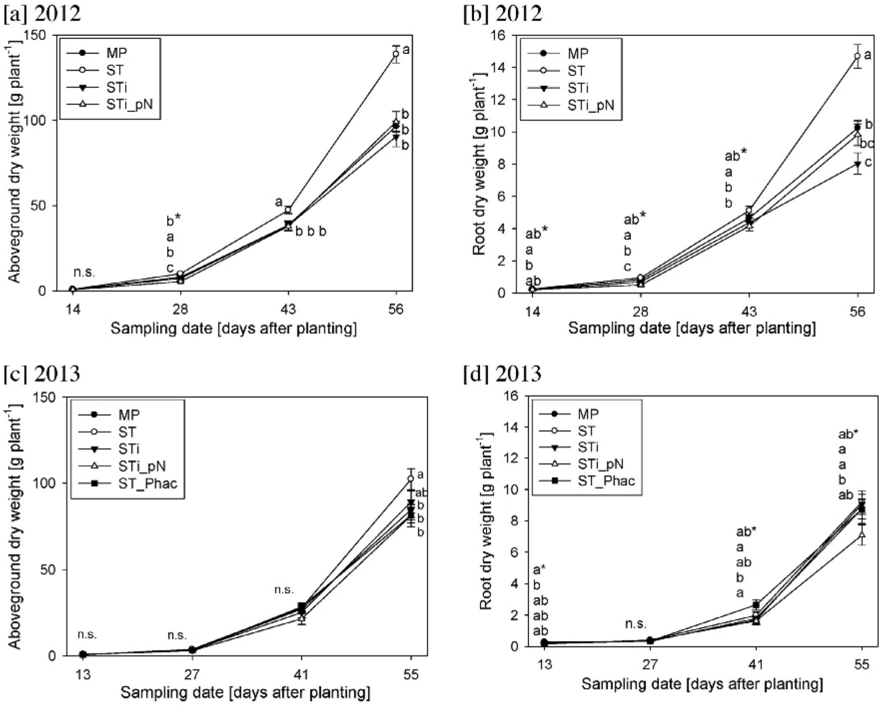

**Fig. 3.** [a] [c] Average aboveground and [b] [d] root biomass (dry weight per plant) of cabbage plants at different sampling dates in 2012 and 2013. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; ST_pN: intensive strip-tillage with a band-placed nitrogen fertilization. ST_Phac: strip-tillage with *Phacelia* as cover crop. No significant differences for values with same letters, $P < 0.05$. Vertical bars indicate standard error of means. Each sampling date was analyzed separately. *Order of significance letters according to the legend order.

all sampling dates and for 2013 at the last sampling date before harvest (Fig. 3a and c).

In 2012, for root biomass, there was also significantly higher biomass under ST (14.2 g plant$^{-1}$) compared to all other treatments at the last sampling date. For the first three sampling dates, the greatest root biomass amounts were also found under ST, but there were no significant differences to MP (Fig. 3b). In 2013, there was no clear trend of the root weight for all sampling dates (Fig. 3d).

### 3.3. Nitrogen content and nitrogen uptake

In both years, the nitrogen content in the cabbage plants increased until four weeks after planting and then decreased until harvest (Fig. 4a and c). N contents at early stages varied between 4.7% (MP) and 6.5% (STi_pN) in 2012 and between 3.4% (STi_Phac) and 5.8% (STi_pN) in 2013. There were subsequently no more significant differences found between the treatments at later dates during growing season 2012, and at harvest the N contents were about 2.3% (Fig. 4a). For N content in root biomass, there were also highest values under STi_pN during the entire growing season, excepted 55 dap (data not shown).

In 2013, at the first three sampling dates, the highest N contents were found under STi_pN; however, at harvest time there was the inverse result with the lowest N content found under STi_pN (2.2%) (Fig. 4c). No clear trends were visible for the root mass (data not shown).

Significantly higher N-uptake in aboveground biomass occurred under ST than under MP until 56 dap in 2012, which ranged from 2 kg N ha$^{-1}$ to 201 kg N ha$^{-1}$, but these differences were leveled out at harvest ST (approx. 290 kg N ha$^{-1}$ in ST and 270 kg N ha$^{-1}$ in MP; Fig. 4b).

In 2013, the treatments had quite similar though significantly different nitrogen uptake, but there was no treatment which always had clearly higher or lower uptake. The highest N uptake at harvest was measured in MP (240 kg N ha$^{-1}$) and ST (230 kg N ha$^{-1}$; Fig. 4d).

### 3.4. Cabbage yield, nitrogen use efficiency and nitrogen budget

The marketable white cabbage yield (fresh weight of cabbage heads without cover leaves) reached the maximum in 2012 in ST (74 t ha$^{-1}$), which was significantly higher than under MP (65 t ha$^{-1}$) and under STi_pN (67 t ha$^{-1}$). The yield potential in 2013 was lower than in 2012 with a range from 50 t ha$^{-1}$ in STi_pN to 58 t ha$^{-1}$ in MP (data not shown). The aboveground dry weights of cabbage plants were significantly higher under ST (311 g plant$^{-1}$) than under MP (280 g plant$^{-1}$) in 2012 and in 2013 there were no significant difference between MP (255 g plant$^{-1}$) and ST (253 g plant$^{-1}$); however, significantly lower dry weights were detected under STi_pN (224 g plant$^{-1}$) compared to MP and ST (Fig. 5).

The NUE (nitrogen use efficiency) of all treatments was higher in 2012 than in 2013. Significantly lower NUE was found 2012 under MP (41.47 kg yield kg$^{-1}$ N) compared to all other treatments. In 2013, in contrast to 2012, highest NUE was detected under MP (38.02 kg yield kg$^{-1}$ N) with significant differences to ST_Phac (34.07 kg yield kg$^{-1}$ N) and STi_pN (33.12 kg yield kg$^{-1}$ N). The

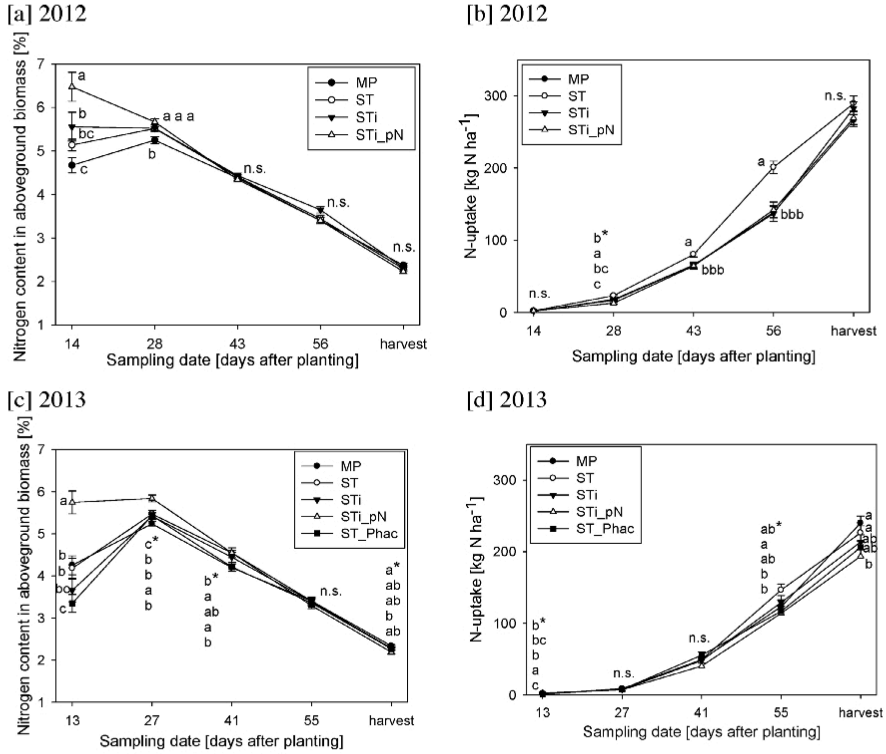

**Fig. 4.** [a] [c] Nitrogen content in aboveground biomass and [b] [d] N-uptake of white cabbage under different soil preparation and different fertilization technique in 2012 and 2013 at four different sampling dates. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; ST_pN: intensive strip-tillage with a band-placed nitrogen fertilization. ST_Phac: strip-tillage with *Phacelia* as cover crop. No significant differences for values with same letters, $P < 0.05$. Vertical bars indicate standard error of means. Each sampling date was analyzed separate from each other. *Order of significance letters according to the legend order.

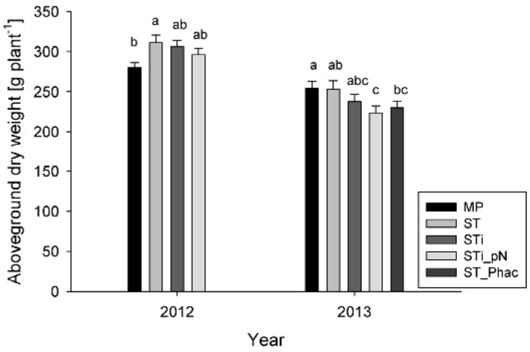

**Fig. 5.** Aboveground dry weight per plant under different soil preparation and fertilization techniques at harvest in 2012 and 2013. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; ST_pN: intensive strip-tillage with a band-placed nitrogen fertilization. ST_Phac: strip-tillage with *Phacelia* as cover crop. No significant differences for values with same letters, $P < 0.05$. Vertical bars indicate standard error of means.

nitrogen budget was negative in 2012 in ST ($-19$ kg ha$^{-1}$) and STi ($-13$ kg ha$^{-1}$). In 2013, there was a surplus of nitrogen throughout the treatments with the highest values under STi_pN (76 kg N ha$^{-1}$) and the lowest under MP (30 kg N ha$^{-1}$) (Table 2).

## 4. Discussion

Tillage systems can influence the nitrogen dynamics in soil (Wienhold et al., 1999). The accumulation of crop residues on the soil surface in conservation tillage often leads to a high C:N ratio and high organic matter content in the top soil and an immobilization of nitrogen due to the incorporation into microbial biomass (Franzluebbers et al., 1995). However, there is no proof from the recent study for this phenomenon. SMN content in MP tended to be lower than in ST in both experimental years. The assumption that mineralization increased under deep soil inversion (MP), accompanied by higher SMN contents (Halvorson et al., 2001), cannot be confirmed. The results, however, reflect only the situation of a very short time of strip-till. Effects of conservation tillage may become visible after long-term reduced tillage (Stubbs et al., 2004). Additionally, the strongest effects on soil characteristics usually occur in the comparison between no-till and conventional tillage; strip-tillage, however, is an intermediately reduced tillage system which also includes soil disturbance; thus,

**Table 2**
Nitrogen use efficiency and nitrogen budget under different tillage treatments at harvest time in 2012 and 2013. MP: moldboard plowing; ST: strip-tillage; STi: intensive strip-tillage; ST_pN: intensive strip-tillage with a band-placed nitrogen fertilization. No significant differences for values with same letters, $P < 0.05$.

| | Nitrogen use efficiency (kg dry matter yield $kg^{-1}$ N supply) | | Nitrogen budget (kg N $ha^{-1}$) | |
|---|---|---|---|---|
| | Experimental year | | | |
| | 2012 | 2013 | 2012 | 2013 |
| MP | 41.47b | 38.02a | 4a | 30b |
| ST | 46.52a | 37.21ab | −19a | 44bc |
| STi | 45.29a | 35.21abc | −13a | 56ab |
| STi_pN | 44.50a | 33.12c | 1a | 76a |
| ST_Phac | n.d.[a] | 34.07bc | n.d.[a] | 64ab |

[a] n.d.: not detected.

the decrease in mineralization is not very strong. Because of variations of SMN contents dependent on soil types, cropping systems, and climate conditions, the outcome of other research is very variable. In contrary to the recent study, SMN contents tend to be lower with decreased tillage intensity (Brye et al., 2003; Gál et al., 2007; Gruber et al., 2011) or they even found significantly lower SMN contents under reduced tillage or no-till (Franzluebbers and Hons, 1996; Wander and Bollero, 1999). The significantly higher SMN content in STi_pN in the tilled area (IR), compared to the broadcast fertilization in strip-tillage, indicates that the row application of nitrogen actually worked. Another reason for higher SMN contents in STi_pN could be a higher mineralization in the strips due to higher temperatures and aeration of these areas. The introduction of a cover crop in the fall before the cabbage growing period in treatment ST_*Phac* seems likely to be a very useful measure against nitrate leaching over winter as it significantly reduced SMN in spring; this effect is well known and demonstrated by Di and Cameron (2002),Gruber et al. (2011) and Fraser et al. (2013).

There was no confirmation of the hypothesis that the more intensive strip-tillage treatments (STi and STi_pN) would provide more suitable growing conditions by a repeated tillage operation compared to single strip-tillage (ST). The highest aboveground and root biomass of cabbage across all sampling dates in 2012 and across most the sampling dates in 2013 in ST showed a high yield potential already in early stages of development. In comparison to MP, the yield in ST was similar or even higher. These results correspond well to other investigations, which also revealed a high yield potential in strip-tillage system compared to no-till and conventional tillage (Licht and Al-Kaisi, 2005; Evans et al., 2010; Haramoto and Brainard, 2012). Both in 2012 and 2013, the cabbage yield in STi_pN was lower compared to ST; perhaps, the wet soils, especially in spring 2013, have led to a soil compaction during the second soil loosening in spring. The band-placed nitrogen application could also have resulted in less root development, due to a high nitrogen stock at the beginning of the growing season near to the roots. Nitrogen uptake from the soil at the end of the growing season, when only little N was remaining from fertilization with ENTEC, may have been limited. This explanation is supported by the high nitrogen content in cabbage plants of STi_pN at the beginning of the growing period. The possible benefit through the more frequent soil preparation and the fertilizer placement ultimately could not be utilized by the plants for a higher yield level. The decrease of plant N content during the season is similar to Walker et al. (2001), who explained the decreasing N contents by a dilution effect from growth and an increase in the amount of structural material. Although the total nitrogen content in plants is often described to be higher in conservation tillage systems compared to conventional tillage (Angle et al., 1993), the recent study did not show the same effect. The reason might – as for SMN – be the fact that strip-tillage is obviously a very moderate way of conservation tillage which retains many beneficial effects from conventional tillage. This is exactly the benefit, which is expected from strip-tillage as a combination of no till and soil disturbance.

The N-uptake in ST which was significantly higher than in MP and STi_pN is a further indication that the cabbage plants in strip-tillage were obviously able to take up the nitrogen, not only from the tilled area, but also from the non-tilled area. Investigations of the N-uptake by different tillage practices resulted in different findings. No influence from the different tillage practices, if no-till, strip-tillage, and chisel till were compared, was detected for the N-uptake in cotton, sorghum (Sainju et al., 2007), and corn (Al-Kaisi and Licht, 2004), whilst other experimental results showed a nutrient deficiency in no-till or conservation tillage experiments compared to conventional tillage (Mehdi et al., 1999). The broadcast application was superior to the band-placed application in the recent study; however, in investigations in the Netherlands, the N-uptake and yield of cabbage was not affected by a fertilizer placement (Everaarts, 1993; Neeteson, 1995), or an even higher plant N content was measured under band-placed nitrogen compared to broadcast in corn and barley (Maddux et al., 1991; Malhi and Nyborg, 1991). For a final assessment of the effect of nitrogen placement, the general conditions of this method in strip-tillage, such as soil water, soil temperature, and form of nitrogen, would have to be analyzed more deeply.

The nitrogen use efficiency (NUE) and the nitrogen budget are often used as indicators of a cropping system's ability to maintain soil fertility and water quality (Grignani et al., 2007). The results of NUE and especially of the nitrogen budget indicate that there was no overfertilization in all treatments, because in 2012 there is no surplus and also in 2013 the surpluses of nitrogen provide no indication of high risk of nitrate leaching over winter. The results of the recent study are similar to investigations in Denmark with different vegetables which showed an efficient N-uptake and low nitrogen losses by nitrate leaching under white cabbage, because of a low N supply at harvest time (Kristensen and Thorup-Kristensen, 2004). Additionally, the treatment STi_pN had no positive effect on the NUE, despite positive findings previously reported by Everaarts et al. (1996). For the present investigation, the nitrogen budget was only significantly affected by the tillage system only in 2013. In contrast, other investigations and the results from this current study in its first experimental year showed no effect of the N-budget caused by different tillage systems (Sieling and Kage, 2010).

All in all, in contrast the stated hypothesis, broadcast nitrogen fertilization was not inferior to band-placed fertilization, and two times of strip-tillage had no yield advantage for white cabbage. Strip-tillage for white cabbage does not seem to be linked with major yield-limiting effects.

## 5. Conclusions

Strip-tillage seems to be a suitable alternative to conventional tillage for field grown vegetables such as white cabbage. The simple, single strip-till operation in fall and a broadcast N application might be sufficient enough; any need for two times tillage and placed N fertilization cannot be deduced from these experiments. Strip-tillage, with all the advantages over the moldboard plow in terms of soil protection, can be used to grow cabbage with almost the same yield potential as in tillage system with the moldboard plow. After combining the benefits from no-till and inversion tillage practices, overall these findings may also be applicable to other vegetable species which have similar requirements to that of white cabbage with regards to the growth and soil conditions.

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# 6 Evaluation of the CROPGRO model for white cabbage production under temperate European climate conditions

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*Plant growth simulation models are valuable tool to predict yield potential under different management scenarios and different environmental conditions. The process-oriented crop growth simulation model CROPGRO which is embedded in the Decision Support System for Agrotechnology Transfer (DSSAT) modeling package was originally developed for legume crops. The generic nature of CROPGRO allowed the integration of other crops including vegetables, such as tomato, sweet corn or cabbage. However, until recently, the application of these models has not been very wide spread. For this reason, the objective of this publication was to evaluate the CROPGRO cabbage model for cabbage production under temperate European climate conditions. This was undertaken using a data collection of the different cabbage growth parameters measured from the presented field experiments. Furthermore, data sets from two other German locations were provided so that an evaluation of the model could be undertaken.*

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# Evaluation of the CROPGRO model for white cabbage production under temperate European climate conditions

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ABSTRACT

The CROPGRO cabbage model, included in the Decision Support System for Agrotechnology Transfer (DSSAT) software, was initially calibrated under tropical Hawaiian climate conditions. Until recently, the application of this model has not been very widespread. Hence, the main objective of this study was to evaluate the CROPGRO cabbage model for white cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.) production under temperate European climate conditions. Data sets of field experiments from southwest Germany were used for model calibration including observed data of number of leaves, leaf area index, specific leaf area, leaf and stem weight, head weight and total aboveground biomass. For model evaluation, cabbage data sets over three years from southeast and over two years from east Germany were used. The genotype files (cultivar and ecotype), which include the main parameters of crop phenology and plant growth, were adapted to the standard European cabbage cultivar 'Kalorama'. Observed dry matter cabbage head yields over different years and different locations ranged between 6574 kg ha$^{-1}$ and 11926 kg ha$^{-1}$; head yields over all datasets were predicted by the model with an accuracy of $R^2 = 0.98$. Sensitivity analysis conducted under different nitrogen fertilizer amounts (−50% N to +50% N) and two fertilizer application strategies (basal and split) generated logical, useful results from an agronomic point of view. The sensitivity analysis revealed that the efficiency of nitrogen fertilization highly depends on the genetically determined potential yield of a specific cabbage cultivar under given environmental conditions. Overall, the CROPGRO cabbage model proved to be suitable for predicting white cabbage yields under temperate European climate conditions and under different management strategies.

## 1. Introduction

In Germany, cabbage crops (*Brassica oleracea* L.) are the third most important vegetables with a production share of 18%, following leafy vegetables (40%) and root and tuber vegetables (25%). White cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.) is the most important subspecies within the *Brassica* family and is grown in Germany on a total area of 5840 ha (Statistisches Bundesamt, 2013). It is a crop with a high nitrogen demand. Recommended fertilizer amounts are between 200 and 500 kg N ha$^{-1}$ for optimal growth and high yields (Zebarth et al., 1991; Sørensen, 1993; Sanchez et al., 1994). Under temperate climate conditions, nitrogen requirements of white cabbage are estimated to range between 240 and 320 kg N ha$^{-1}$ (Feller et al., 2011) for a mean cultivation period of 65–150 days. To minimize the risk of nitrate leaching that would result in groundwater pollution and soil degradation, it is necessary to adapt the fertilizer amounts based on yield potential, crop requirements and environmental factors such as soil type and climate conditions (Leenhardt et al., 1998). An effective irrigation system in combination with cultivars having a higher nitrogen use efficiency can reduce the risk of nitrate leaching (Hirel et al., 2007; Agostini et al., 2010). Furthermore, split nitrogen applications can be a valuable measure to meet the nitrogen demand of plants during the cultivation period. For cabbage production, split nitrogen application showed variable effects depending on weather and soil conditions (Welch et al., 1985; Wiedenfeld, 1986; Everaarts and De Moel, 1998). According to several studies (Everaarts and De Moel, 1998), the recommended nitrogen fertilizer amount of approximately 350 kg N ha$^{-1}$ can be reduced without decreasing the yield potential. In addition to the environmental risks of over-fertilization, cabbage head quality can be affected negatively by high nitrate concentrations in the edible parts of the plant, which has been associated with serious health complications, especially for children (Maynard and Barker, 1972).

For the purpose of meeting the cabbage needs in Germany and Europe, it is important to understand interactions between cabbage

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growth and environmental conditions, as well as the nutrient and water demand and their final relation to yield and quality. The fact that field experiments are laborious, costly and time-consuming, makes process-oriented crop simulation models a valuable tool for simulating crop growth, predicting yield potentials and adapting management systems (Boote et al., 1996; Jagtap and Abamu, 2003). Several crop growth simulation models are commonly used and accepted by researchers worldwide (Hoogenboom et al., 2003; Keating et al., 2003; Van Ittersum et al., 2003). The CROPGRO model embedded in the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003) was originally developed to simulate growth of legume crops (Wilkerson et al., 1983; Boote et al., 1987; Hoogenboom et al., 1994). Based on climatic, soil and environmental conditions, CROPGRO is able to simulate the crop response to different fertilizers or the effect of irrigation management strategies (Boote et al., 1998). Furthermore, Liu et al. (2011) applied the model successfully in simulating soil water contents and nitrate leaching.

An important application of this crop growth model is to conduct sensitivity analysis to determine the potential crop yield achievable under specific climate and environmental conditions and under different management strategies. For example, the simulation of crop growth and yield formation under varying amounts of nitrogen fertilizer aids in giving recommendations for the best management practice (Kropff et al., 2001).

The generic nature of CROPGRO allows the integration of other crops including bell pepper (*Capsicum annuum* L.), cabbage (*B. oleracea* L.), tomato (*Lycopersicon esculentum* Mill.; Rinaldi et al., 2007; Boote et al., 2012), sweet corn (*Zea mays* L.; Lizaso et al., 2007; He et al., 2012) and velvet bean (*Mucuna pruriens* L.; Hartkamp et al., 2002a,b). In particular, the CROPGRO cabbage model was established by Hoogenboom et al. (2012) based on datasets from Hawaii, which were collected by Ogoshi, who also created the data files for the integration of the cabbage model into the DSSAT version 4.5. However, to the best knowledge of the authors, no study has been published in which the CROPGRO cabbage model was applied to cabbage grown under temperate climate conditions. The main objectives of the present study were: (i) to calibrate the CROPGRO model for cabbage growth under temperate climate conditions with a standard white cabbage cultivar in southwest Germany, (ii) to evaluate the model with cabbage yield data derived from different German locations over several years; and, (iii) to carry out a sensitivity analysis with different nitrogen fertilization amounts and two different fertilization strategies to investigate whether the applied fertilizer amounts can be optimized for achieving high yield levels.

## 2. Material and methods

### 2.1. Field experiments and data collection at Ihinger Hof

The data sets used for model evaluation were derived from field experiments in 2012 and 2013 carried out at the experimental station 'Ihinger Hof' of the University of Hohenheim (48°44′N, 8°55′E, 478 m a.s.l.) in southwest Germany. The average yearly rainfall is around 690 mm with an average temperature of 8.1 °C and a mean solar radiation of 11.4 MJ m$^{-2}$ d$^{-1}$. Weather data was available from a weather station adjacent to the experimental field (Fig. 1a). The soil, classified as Haplic Cambisol Ruptic (loess above upper triassic), is a clay loam soil type with a clay content of approximately 29% (CL; FAO, 2006). Tillage operation was conducted with a moldboard plough in autumn 2011 and 2012 (21 cm deep). Soil samples were taken in spring 2012 and 2013 to determine the soil mineral nitrogen content from 0 to 90 cm soil depth according to the IGZ (Leibniz-Institut für Gemüse- und Zierpflanzenbau Großbeeren/Erfurt e.V.) fertilizer recommendation system for white cabbage (Feller et al., 2011). Taking the determined soil mineral nitrogen content into account, the ammonium nitrate fertilizer ENTEC perfect (15% N + 5% $P_2O_5$ + 20% $K_2O$) was applied to a target value of 270 kg N ha$^{-1}$. N-fertilizer was broadcast and incorporated with a rotary harrow one day before transplanting.

White cabbage cv. Kalorama was transplanted 50 × 50 cm with a total-controlled transplanter (Checchi & Magli, Italy) on 14 May 2012 and 15 May 2013. Number of leaves and dry weight of ten plantlets were determined on the transplanting date. During the growing period, destructive plant samplings were conducted 11, 39, 56 and 99 days after transplanting (DAP) in 2012, and 34, 48 and 62 DAP in 2013. Three cabbage plants per repetition were separated into leaf, stem and head. For the first three samplings, the leaf area of each plant was measured (LI-3100 Area Meter; LI-COR, Lincoln, Nebraska, USA). In addition, in 2013, 27, 34, 41, 48, 54 and 62 DAP, leaf number, plant height and diameter (perpendicular to the row orientation) of five plants per repetition were measured non-destructively. At final harvest on 1 October 2012 (140 DAP) and 10 October 2013 (148 DAP), total aboveground fresh weight of 45 plants was measured. Additionally, fresh marketable head weight was determined after the removal of cover leaves. All plant samples were dried at 60 °C until constant weight and dry matter was determined.

### 2.2. Data sets from two cabbage production areas of Germany

For model evaluation, cabbage yield data sets from two locations in southeast and eastern Germany, namely Landau an der Isar (48°36′N, 12°43′E, 380 m a.s.l.) and Erfurt (50°98′N, 10°96′E, 316 m a.s.l.), were used. The datasets were derived from trial reports of the Bavarian Regional Institute for Viticulture and Horticulture (Küster, 2010a,b; Göttl, 2011; Eberl, 2012) and of the Research Institute for Horticulture Erfurt (Krumbein and Germanus, 2001, 2002). At each location, the field experiments were conducted with the same cultivar (Kalorama) as used at the experimental location Ihinger Hof Field trials were conducted in 2000 and 2001 in Erfurt, and from 2010 to 2012 in Landau, respectively. The soil at Erfurt is classified as a silty loam (SiL) with a clay content of 10% and at Landau also as a silty loam in 2010 and a sandy loam (SL) in 2011 and 2012 with 10% clay. Over the duration of the experiment, the average annual temperature in Landau was 8.5°C and for Erfurt 9.1 °C. The annual precipitation was 761 mm in Landau and 496 mm in Erfurt (Fig. 1b and 1c). The average annual solar radiation was 11.5 MJ m$^{-2}$ d$^{-1}$ in Landau and 10.6 MJ m$^{-2}$ d$^{-1}$ in Erfurt. At both locations, nitrogen fertilization was split into three to five applications with a total amount ranging between 250 and 360 kg N ha$^{-1}$ (Table 1). At Erfurt, white cabbage seedlings were transplanted with a row distance of 60 cm × 40 cm on 21 June 2000 and 6 June 2001. In contrast, at Landau, white cabbage was seed-sown with a sowing density of 4.8 seeds m$^{-2}$ on 28 April 2010, 21 April 2011 and 19 April 2012.

For evaluation of the CROPGRO cabbage model, the average marketable fresh matter head weight was converted to dry matter yield with a standard value for cabbage dry matter of 10.7% measured in the experiments from 2012 to 2013 at Ihinger Hof. Final harvests were conducted at Erfurt on 29 October 2000 and on 5 October 2001; and at Landau on 13 October 2010, 5 October 2011, and 2 October 2012.

### 2.3. Model description and calibration

The CROPGRO model comprises of three genotype files, namely cultivar, ecotype and species files, which include the main parameters to describe crop phenology and plant growth (Hoogenboom et al., 2003). The CROPGRO cabbage model, included in the DSSAT

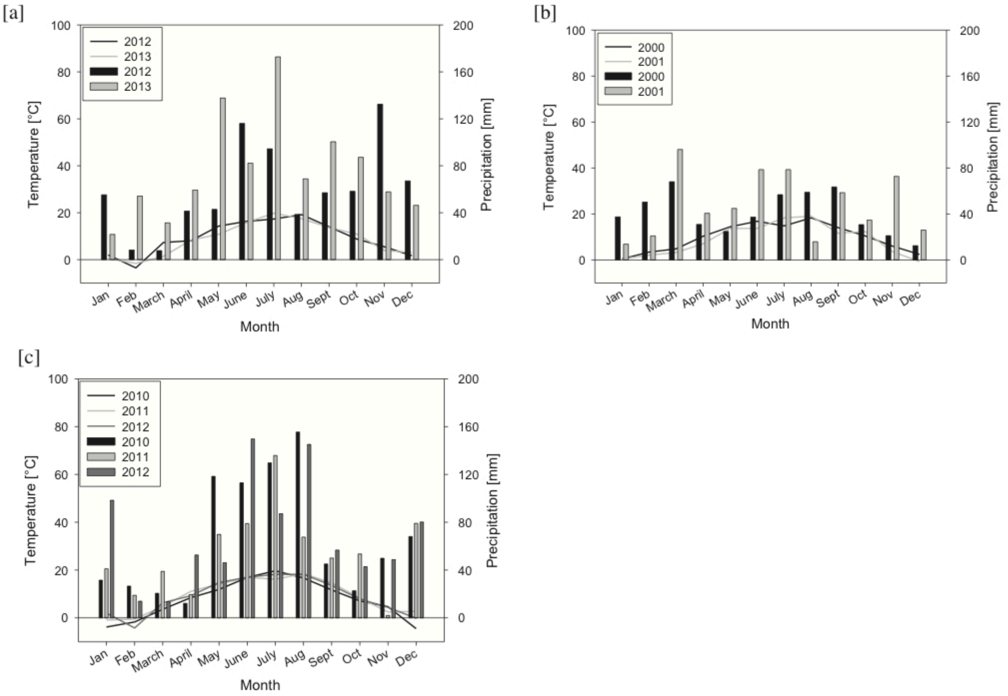


**Fig. 1.** Monthly average air temperature (°C, lines) and precipitation rates (mm, bars) at the experimental sites [a] Ihinger Hof (2012, 2013), [b] Erfurt (2000, 2001) and [c] Landau (2010–2012).

software, was initially calibrated under tropical Hawaiian climate conditions for the cabbage cultivar Tastie (Hoogenboom et al., 2003). For the calibration of a typical cabbage cultivar for temperate European climate conditions (Kalorama), several cultivar and ecotype coefficients were adapted systematically according to Boote (1999) using the collected dataset of Ihinger Hof in 2013 until observed and simulated values showed a high agreement based on the lowest root mean square error (RMSE). Observed data of number of leaves, leaf area index, specific leaf area, leaf and stem weight, canopy dimensions (height and width), head weight and total aboveground biomass were included.

### 2.4. Model application for different N fertilizer amounts and application strategies

A sensitivity analysis was conducted to assess the effects of different N fertilizer amounts and two different application strategies, namely basal and split application. The different nitrogen fertilizer amounts were based on the experimental N fertilizer amounts (exp.) at Ihinger Hof, Erfurt and Landau. Simulations were run for each location and year with the experimental N-fertilizer amount changed by ±10%, ±20%, ±30%, ±40% and ±50%. Simulations with reduced and increased fertilizer amounts were carried out both with a split application and a basal application strategy, based on the experimental application dates and fertilization amounts (Table 1). At Ihinger Hof, the fertilizer application was conducted with a basal application one day before transplanting. For the sensitivity analysis, the total N-fertilizer amount was split into three rates and applied at one day before transplanting, 32 DAP and 64 DAP. At Erfurt and Landau, there was a split N-fertilization in the field experiments. For the sensitivity analysis, the different amounts were summed up for the simulations with a basal fertilization. Furthermore, nitrate-N loss through leaching as simulated by the CROPGRO model was available for further interpretation of results.

### 2.5. Model evaluation

The model was evaluated by the comparison of observed and simulated values using the statistical indices root mean square

**Table 1**
Irrigation (mm) and nitrogen fertilization (kg ha$^{-1}$) at Ihinger Hof (2012, 2013), Erfurt (2000–2001) and Landau (2010–2012).

| | Ihinger Hof | | Erfurt | | | Landau | |
|---|---|---|---|---|---|---|---|
| | 2012 | 2013 | 2000 | 2001 | 2010 | 2011 | 2012 |
| Total irrigation (mm) | 120 | 10 | | 230 | 30 | 50 | 24 |
| Basal N-application (kg ha$^{-1}$) | 240 | 240 | 150 | 150 | 72 + 100 | 120 | – |
| Top N-application(kg ha$^{-1}$) | – | – | 50 + 50 | 50 + 50 | 55 + 55 + 30 | 60 + 90 + 90 | 123 + 80 + 65 |
| Total N-application (kg ha$^{-1}$) | 240 | 240 | 250 | 250 | 312 | 360 | 268 |

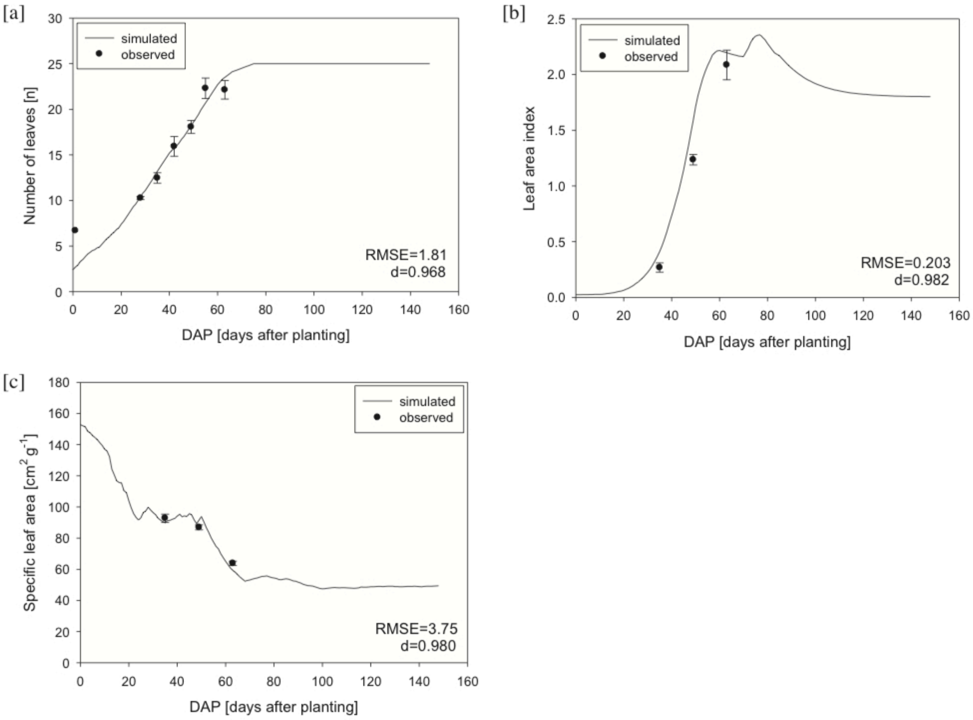


**Fig. 2.** Simulated (line) and observed (points) number of leaves [a], leaf area index [b] and specific leaf area [c] of cabbage used for model calibration based on the data set of 2013 from Ihinger Hof; vertical bars represent the standard error of the observations, root mean square error (RMSE) and index of agreement (d).

error (RMSE) and the index of agreement (*d*; Willmott, 1981) according to following formulas:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \quad (1)$$

$$\text{Index of agreement } (d) = 1 - \left[\frac{\sum_{n=1}^{n}(S_i - O_i)^2}{\sum_{n=1}^{n}\left(\left|S_i'\right| - \left|O_i'\right|\right)^2}\right] \quad (2)$$

where $S_i$ represents the simulated and $O_i$ the observed values, n the number of observations, $\left|S_i'\right|$ the difference between $S_i$ and the mean of the simulated values, and $\left|O_i'\right|$ the difference between $O_i$ and the mean of the observed values.

## 3. Results and discussion

### 3.1. Model calibration

Several parameters of the cultivar and the ecotype file, initially calibrated for the cultivar Tastie, were adapted to the European standard cultivar Kalorama (Table 2). First, parameters responsible for plant phenology were adapted. Based on collected datasets, the growing period was elongated by increasing the parameter SD-PM (photothermal days from first seed to physiological maturity) from 55 to 82 and the time until head initiation (FL-SH) was slightly increased from 5.0 to 6.0. Second, simulations of the leaf area development were adjusted by increasing the leaf appearance rate on the main stem (TRIFOL) from 0.38 to 0.45 and by considerably decreasing the specific leaf area (SLAVAR) from 220 to 80 cm$^2$ g$^{-1}$. In addition, overestimations of the initial increase of the LAI were accounted for by decreasing the maximum size of the first three fully developed leaves (SIZLF) from 50 to 20 cm$^2$. Furthermore, the end of leaf appearance and leaf area expansion were adjusted by shortening the time until the last leaf is developed on the main stem after flowering (FL-VS, photothermal days) from 35 to 23 and the time to cessation of leaf area expansion (FL-LF, photothermal days) from 42 to 20. The increases of canopy dimensions (height and width) were adjusted by increasing the parameters of relative width (RWIDTH) and the relative height (RHGHT) of this ecotype in comparison to the standard width and height per node defined in the species file. Finally, the partitioning of assimilates to the cabbage head (XFRT) was slightly increased and the maximum weight per seed (WTPSD) was decreased from 0.25 to 0.19 g. Underestimations of the dry matter of all plant organs were accounted for by increasing the maximum leaf photosynthesis rate (LFMAX, mg CO$_2$ m$^{-2}$ s$^{-1}$) from 1.030 to 1.250.

The calibration led to a high accuracy of the simulations with indices of agreement (*d*) above 0.94 for most of the parameters observed (Fig. 2). The simulation of number of leaves showed, in general, a high accuracy for all sampling times, with the exception of an underestimation on the day of transplanting with a predicted value of 2.4 compared to the observed value of 6.7 (Fig. 2a). The transplant option within the crop management tool does not account for a transplanting shock and does not provide an option to

**Table 2**
Cultivar coefficients of the white cabbage cultivar 'Kalorama', which were changed compared to cabbage cultivar 'Tastie'.

| File | Description of variable | Value | |
|---|---|---|---|
| Cultivar coefficients | | Cabbage cv. 'Tastie' | Cabbage cv. 'Kalorama' |
| FL-SH | Time between first flower and first pod (R3) (photothermal days) | 5.0 | 6.0 |
| FL-SD | Time between first flower and first seed (R5) (photothermal days) | 11 | 16 |
| SD-PM | Time between first seed and physiological maturity (R7) (photothermal days) | 55 | 82 |
| FL-LF | Time between first flower (R1) and end of leaf expansion (photothermal days) | 42 | 20 |
| LFMAX | Maximum leaf photosynthesis rate at 30 °C, 350 vpm $CO_2$, and high light (mg $CO_2$ $m^{-2}$ $s^{-1}$) | 1.030 | 1.250 |
| SLAVR | Specific leaf area of cultivar under standard growth conditions ($cm^2$ $g^{-1}$) | 220 | 80 |
| SIZLF | Maximum size of full leaf (three leaflets) ($cm^2$) | 50 | 20 |
| XFRT | Maximum fraction of daily growth that is partitioned to head | 0.600 | 0.650 |
| WTPSD | Maximum weight per seed (g) | 0.25 | 0.19 |
| Ecotype coefficients | | | |
| FL-VS | Time from first flower to last leaf on main stem (photothermal days) | 35.0 | 23.0 |
| TRIFOL | Rate of appearance of leaves on the main stem (leaves per thermal day) | 0.38 | 0.45 |
| RWDTH | Relative width of this ecotype in comparison to the standard width per node (YVSWH) defined in the species file | 1.0 | 1.8 |
| RHGHT | Relative height of this ecotype in comparison to the standard height per node (YVSHT) defined in the species file | 1.0 | 1.2 |

determine the number of leaves (Salam et al., 2001). The latter could further improve simulations of the leaf number when transplants are used.

Leaf area index (Fig. 2b) and specific leaf area (Fig. 2c) showed a high accuracy between observed and simulated values, indicated by a low RMSE of 0.2 and 3.75.

Simulations of dry matter partitioning among leaves and stem matched the observed data well, as indicated by low RMSEs and high indices of agreement for both parameters (Fig. 3a and b). Dry matter head yield was simulated with a very high accuracy, only showing low underestimation at the beginning of head formation (Fig. 4a). The increase of total aboveground dry matter yield was captured well by the simulations apart from slight underestimations at final harvest time (Fig. 4b).

### 3.2. Model evaluation

For model evaluation, simulations were run for Ihinger Hof (2012), Erfurt (2000–2001) and Landau (2010–2012) with the previously described calibration, without further changes of the calibrated model parameters. Simulations for Ihinger Hof in 2012 were evaluated for leaf area index, dry matter head yield and total aboveground dry matter. Leaf area index was simulated very well, with an index of agreement of 0.97 (Fig. 5a). Simulations for the total aboveground dry matter showed a high accuracy for the observed values during early growing stages. Afterwards, there was first an overestimation of the total dry matter in the midseason, followed by an underestimation at harvest time (Fig. 5b). The overestimation of the total cabbage dry weight in the midseason most likely led to a simulated higher water extraction of soil water by the plants with the result of underestimated yields at the end of the growing season. In addition, model simulations for dry matter head yield were evaluated across the different locations and years, namely Ihinger Hof (2012) and Erfurt (2000, 2001) and Landau (2010–2012). Simulations showed a high accuracy between simulated and observed head yield with an $R^2$ of 0.98 (Fig. 6). Observed yields over the three different locations ranged between 6574 kg $ha^{-1}$ in 2012 at Ihinger Hof and 11,926 kg $ha^{-1}$ in 2011 at Landau. Minor overestimations of the cabbage yields were detected in 2000 at Erfurt and in 2012 at Ihinger Hof. Simulated head yield at Ihinger Hof was 6652 kg $ha^{-1}$ and at Landau 7552 kg $ha^{-1}$ compared to the observed values of 6574 kg $ha^{-1}$ and 7190 kg $ha^{-1}$. At Landau, head yield was slightly underestimated in 2011 with a simulated value of 10,893 kg $ha^{-1}$ compared to the observed value of 11,926 kg $ha^{-1}$. In general, the results indicate that the model is highly suitable for simulating head yield across different locations and years under temperate climate conditions. The lower yield potential in Erfurt compared to Landau was possibly triggered by the lower water availability, with mean annual rainfall rates of 492 mm (2000) and 581 mm (2001). At Ihinger Hof, the lower yield

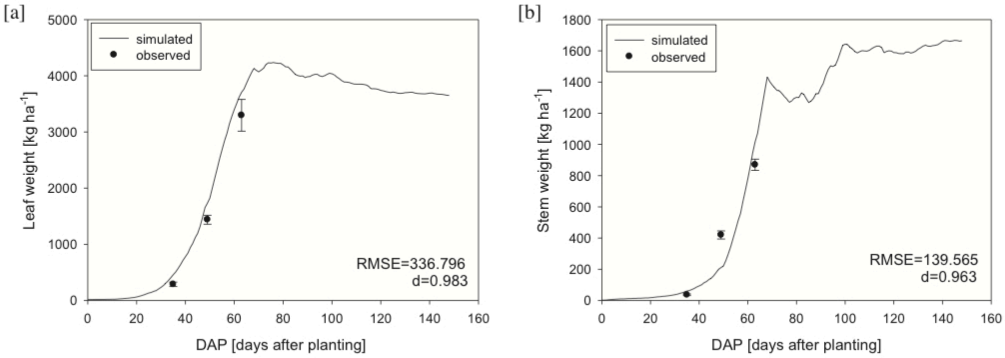


**Fig. 3.** Simulated (line) and observed (points) leaf [a] and stem [b] dry weight of cabbage used for model calibration based on the data set of 2013 from Ihinger Hof; vertical bars represent the standard error of the observations, root mean square error (RMSE) and index of agreement (d).

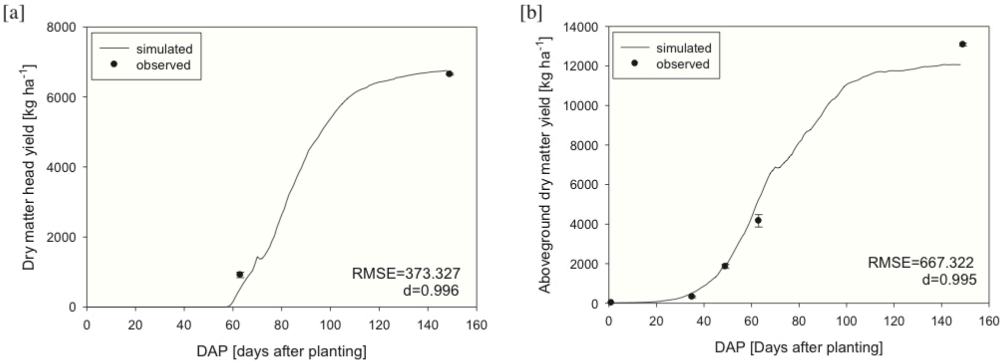


**Fig. 4.** Simulated (line) and observed (points) head yield [a] and total aboveground [b] dry matter of cabbage used for model calibration based on the data set of 2013 from Ihinger Hof; vertical bars represent the standard error of the observations, root mean square error (RMSE) and index of agreement (d).

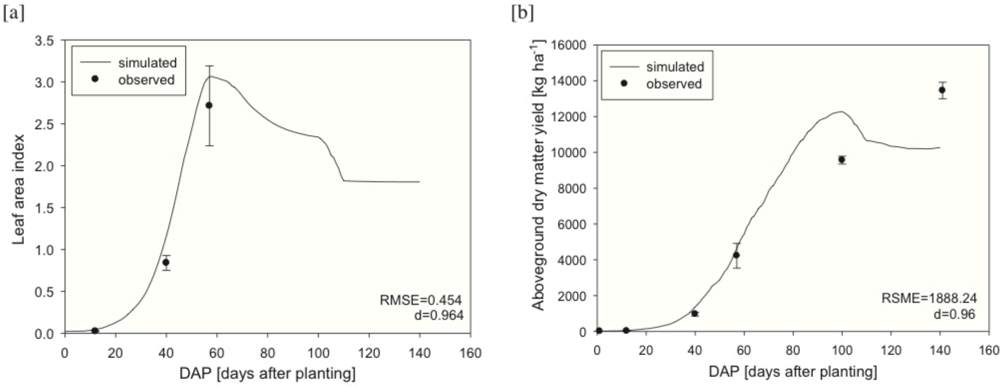


**Fig. 5.** Simulated (line) and observed (points) leaf area index [a] and aboveground dry matter [b] of cabbage for model validation based on the data set from Ihinger Hof in 2012. Vertical bars represent the standard error of the observations, root mean square error (RMSE) and index of agreement (d).

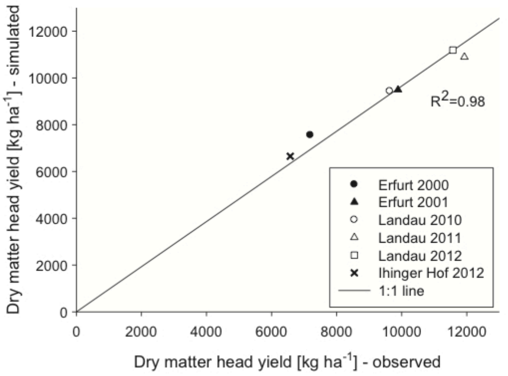


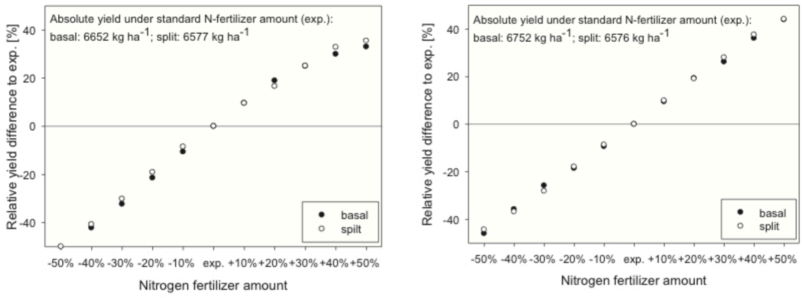
**Fig. 6.** Comparison of simulated and observed dry matter head yield of cabbage for Ihinger Hof (2012), Erfurt (2000, 2001) and Landau (2010–2012). The solid line represents the 1:1 line.

level compared to the other two locations was predominantly due to the low nitrogen supply at the end of growing period with soil mineral nitrogen values of less than 20 kg N ha$^{-1}$.

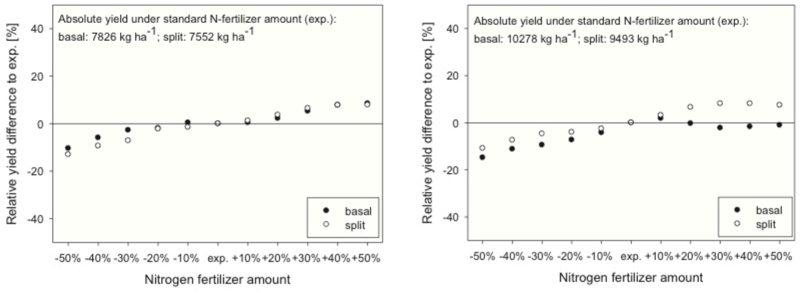
### 3.3. Sensitivity of the N-fertilizer amounts

To reduce environmental burden such as groundwater pollution or soil degradation by over-fertilization, the nitrogen fertilizer amounts should be adjusted to local soil and weather conditions, keeping in mind the goal of achieving high yields. For this reason, a sensitivity analysis was conducted with different fertilizer amounts and different application strategies. In general, the simulations showed different yield potentials with the lowest yield level at Ihinger Hof, followed by Erfurt and Landau. For almost every location and year, the simulations showed increasing yields with increasing fertilizer amounts and decreasing yields with decreasing fertilizer amounts. The simulations corresponded to the results of a number of field experiments, which have also found higher yields under increasing nitrogen fertilization (Pedreño et al., 1996; Wang and Li, 2004; Rosen et al., 2005). At Ihinger Hof, the different amounts of nitrogen fertilizer had the strongest effect on cabbage yield. Under reduced nitrogen fertilization (−50% N) cabbage yield

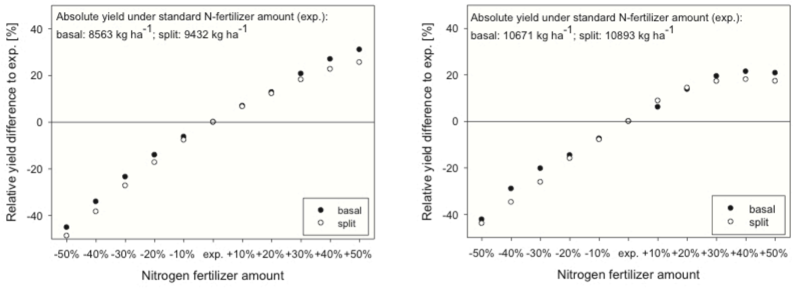
[a] Ihinger Hof ,2012 [b] Ihinger Hof, 2013



[c] Erfurt, 2000 [d] Erfurt, 2001



[e] Landau, 2010 [f] Landau 2011



[g] Landau, 2012

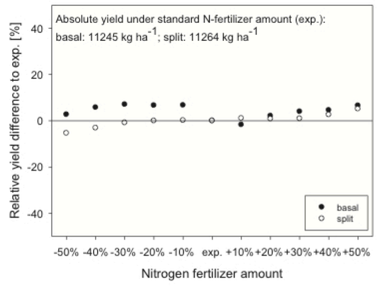


**Fig. 7.** Sensitivity analysis for the effects of different nitrogen fertilization amounts (−50 to +50%) and application strategies (basal, split) on dry matter head yields at Ihinger Hof in 2012 [a] and 2013 [b], Erfurt in 2000 [c] and 2001 [d] and Landau in 2010 [e], 2011 [f] and 2012 [g] in percentage of the simulated yield with the experimental fertilizer amounts (exp.): Ihinger Hof: 240 kg N ha$^{-1}$; Erfurt: 250 kg N ha$^{-1}$; Landau: 2010: 312 kg N ha$^{-1}$; 2011: 360 kg N ha$^{-1}$ and 2012: 268 kg N ha$^{-1}$.

**Table 3**
Simulated cumulative nitrate-N losses (kg N ha$^{-1}$) with different nitrogen fertilizer amounts (−50 to +50%) and different application strategies (basal, split) at Ihinger Hof (2012 and 2013), Erfurt (2000 and 2001) and Landau (2010, 2011 and 2012). Experimental fertilizer amounts (exp.): Ihinger Hof: 240 kg N ha$^{-1}$; Erfurt: 250 kg N ha$^{-1}$; Landau: 2010: 312 kg N ha$^{-1}$; 2011: 360 kg N ha$^{-1}$ and 2012: 268 kg N ha$^{-1}$.

| | Ihinger Hof | | | | Erfurt | | | | Landau | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2012 | | 2013 | | 2000 | | 2001 | | 2010 | | 2011 | | 2012 | |
| | Basal | Split | Basal | Split | Basal | Split | Basal | Split | Basal | Split | Basal | Split | Basal | Split |
| Nitrate-N (kg N ha$^{-1}$) | | | | | | | | | | | | | | |
| −50% N | 7.0 | 4.0 | 0.1 | 0.1 | 0 | 0 | 1.1 | 0.9 | 9.9 | 6.5 | 10.4 | 10.4 | 3.7 | 1.4 |
| −40% N | 8.7 | 4.9 | 0.1 | 0.1 | 0 | 0 | 1.4 | 1.0 | 11.4 | 7.5 | 10.4 | 10.4 | 4.5 | 1.7 |
| −30% N | 10.4 | 5.8 | 0.2 | 0.1 | 0 | 0 | 1.8 | 1.1 | 13.0 | 8.6 | 10.3 | 10.2 | 5.4 | 2.0 |
| −20% N | 11.9 | 6.8 | 0.2 | 0.1 | 0 | 0 | 2.0 | 1.3 | 20.6 | 9.6 | 10.4 | 10.4 | 6.2 | 2.3 |
| −10% N | 13.9 | 7.7 | 0.2 | 0.1 | 0 | 0 | 2.1 | 1.7 | 22.9 | 10.7 | 10.5 | 10.4 | 7.0 | 2.6 |
| exp. | 15.8 | 8.8 | 0.2 | 0.1 | 0 | 0 | 2.2 | 1.8 | 25.5 | 11.6 | 10.9 | 10.3 | 7.9 | 2.9 |
| 10% N | 17.7 | 9.9 | 0.3 | 0.2 | 0 | 0 | 2.5 | 1.9 | 28.2 | 12.7 | 11.9 | 10.3 | 8.7 | 3.2 |
| 20% N | 19.6 | 11.0 | 0.3 | 0.2 | 0 | 0 | 2.7 | 2.1 | 31.3 | 13.9 | 12.9 | 10.4 | 9.6 | 3.5 |
| 30% N | 21.6 | 12.1 | 0.3 | 0.2 | 0 | 0 | 2.9 | 2.1 | 34.9 | 15.0 | 14.0 | 10.4 | 10.4 | 3.7 |
| 40% N | 23.5 | 13.2 | 0.3 | 0.2 | 0 | 0 | 3.5 | 2.3 | 39.1 | 16.2 | 15.1 | 10.5 | 11.3 | 4.1 |
| 50% N | 25.5 | 14.3 | 0.3 | 0.2 | 0 | 0 | 4.6 | 2.4 | 44.5 | 17.8 | 16.2 | 10.5 | 12.1 | 4.4 |

was reduced over the two experimental years by an average of 48%, compared to the standard, experimentally used fertilization rate (exp.). Under the highest fertilizer level (+50% N), yield increased by 34% in 2012 and 44% in 2013 (Fig. 7a and b). For the location Erfurt, the yield differences under different fertilizer amounts were less pronounced. For both application strategies and both experimental years, yield increased on average by about 8% under the highest fertilizer level (+50% N) and decreased by about 12% under the lowest fertilizer level (−50% N, Fig. 7c and d). At Landau, yield simulations showed a strong variation across years. In 2010 and 2011, yields increased with increasing fertilizer amounts up to 31% in 2010 and 21% in 2011. An average yield reduction of 45% (2010 and 2011) was observed with a 50% lower fertilizer amount. In 2012, the yield differences were low, with an average yield increase of only 7% under the highest fertilizer level (+50% N; Fig. 7e and f). The sensitivity analysis at Ihinger Hof showed a strong potential to increase the cabbage yields by increasing amounts of nitrogen fertilizer. The cabbage yield increased up to the potential yield, which is theoretically achievable for this specific cultivar under the given climate conditions. The reason for these strong yield deviations and the strong influence of N fertilization could be the lower nitrogen availability caused by comparatively low mineral nitrogen contents in the soil at this location. Fertilization experiments in Brassicas showed also a strong effect of increasing N-fertilization rates on yield under low soil mineral nitrogen contents (Everaarts, 1993). At Erfurt, the simulated cabbage yield was less influenced by nitrogen fertilization in both experimental years. These results were primarily an effect of water shortage rather than of the varying fertilizer amount. At Landau, the yield level was the highest among the three locations. In the simulations for 2010 and 2011, yield was influenced by different fertilizer amounts; whereas, in 2012 the effect of fertilization was less. This reduced influence of fertilization can be explained by optimal climate conditions (high rainfall, high temperature, high solar radiation) in 2012 resulting in high yield, which was close to the potential yield of this cultivar, so that the high nitrogen fertilization had no further effect. In conclusion, the results of the sensitivity analysis indicated that the efficiency and the effect of the nitrogen fertilization on yield are strongly dependent on the genetically determined potential yield of the specific cultivar and the climate conditions of the locations.

The simulated cabbage yield level showed a minor response to the different application strategies. These simulations agree with results of field experiments conducted with split fertilizer application in cabbage, which also showed no significant effect on cabbage yields (Everaarts and De Moel, 1998). However, with increasing N fertilizer amounts, the risk of nitrate leaching increases (Bergström and Kirchmann, 2004), which was also reflected by the simulations of nitrate-N losses in the present study (Table 3). The simulations indicated a lower risk of nitrate-N losses with split fertilizer application compared to the basal application. Highest nitrate-N losses with split application were simulated in Landau 2010 (+50% N) with 17.8 kg N ha$^{-1}$ compared to 44.5 kg N ha$^{-1}$ under the basal fertilizer application. There is strong evidence that the differences in nitrate-N losses between the years and the locations are, apart from the varying fertilizer amounts, related to different irrigation and precipitation amounts. High precipitation, irrigation and fertilization amounts at Landau and Ihinger Hof correlated with high nitrate-N losses. Under field conditions, high nitrate leaching rates were found with excessive irrigation or high precipitation rates (Leenhardt et al., 1998; Behera and Panda, 2009).

The simulated values of cabbage yield and nitrate-N losses illustrate the conflict between high yielding crops and sustainable fertilizer management. In addition to the risk of nitrate leaching, it should be considered that under field conditions, high nitrogen fertilizer amounts could provoke a reduced quality of the cabbage heads. Decreasing Vitamin C contents and lower glucosinulate concentrations have been measured under high nitrogen fertilization amounts (Rosen et al., 2005; Staugaitis et al., 2008). Furthermore, highly fertilized crops are more susceptible to pathogens and insect pests (Altieri et al., 1998; Walters and Bingham, 2007).

## 4. Conclusions

Results of the study showed that the CROPGRO cabbage model is able to simulate growth and yield formation of white cabbage under temperate European climate conditions. The conducted sensitivity analysis generated logical estimates, which indicates the models' applicability to test different nitrogen fertilizer amounts and application strategies. In addition, the results clarified the importance of a site-specific N fertilization according to soil and climate conditions and the potential yield of the different cultivars. Overall, the CROPGRO cabbage model can be a helpful tool for decision support and farmers' recommendations, and help to adapt the management strategies for a sustainable, high-yield cabbage production.

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# 7 General discussion

This chapter aims to connect the results of the four scientific articles (publications I-IV) and deals with the overall outcome of the thesis and project. Detailed discussion of the results is integrated into each scientific article. In this chapter, the soil erosion control strategies, which were developed and tested within this study, are evaluated in terms of an agronomic and economic point of view and the practicability and farmers' acceptance are discussed. Finally, perspectives of the modeling approach with the process-oriented plant growth simulation model CROPGRO for white cabbage are presented.

## 7.1 Evaluation of soil erosion control strategies for field grown vegetables

The project "Development of erosion control strategies for field grown vegetables" and this thesis focused on the development and the improvement of soil erosion control strategies, especially for field grown vegetables. In particular, three years of field experiments were conducted to test the suitability of row covers (fleece and nets) and to develop and adapt the strip-tillage system for white cabbage.

### 7.1.1 Row covers

Row covers, such as fleece and nets are originally used as frost protection in spring and to accelerate plant growth or used as a protection against insects and birds, particularly in organic farming. Within this study, the row covers were used as erosion control measure in white cabbage (publication I). Row covers showed sufficient erosion control under artificial rainfall simulation, with an average reduction of soil loss under net cover by 48% and under fleece cover about 76%. Furthermore, row covers led to higher **temperatures** and higher relative **humidity**, especially under fleece cover, compared to uncovered plots. Increased risk of plant diseases as a result of the changed microclimate under row covers was detected in the first experimental year, with a higher incidence of *Sclerotinia sclerotiorum* infection on cabbage heads which were covered by fleece. Favorable growing conditions under the row covers were detected by increased leaf area index and higher biomass production, and finally resulted in similar or even higher yields compared to the non-covered control. The results of the field experiments are supported by the findings of other studies, with overall findings of high erosion control (Giménez-Morera et al., 2010), favorable growth conditions (Gimenez et al., 2002) and higher pest incidences under row covers (Jenni et al., 2003).

**Weed control** under row covers, on the other hand, can create a serious problem because the warmer environment leads to earlier germination of weed seeds and the rapid growth of weeds once they have emerged. Options for weed control are limited to preplanting, early-season control in the form of non-selective herbicides or pre-emergence herbicides, which have to be applied before covering the field with fleece or nets. Post-emergence applications without removing the row covers are usually not effective. If row covers are removed before herbicide application and placed back immediately after the application, the activity of the herbicide can be changed due to the modified microclimate under covers (Bonanno, 1996). Alternatively, mechanical weed control by a mechanical hoe or hand-weeding can be conducted after removing the row covers. Thus, weed control remains a challenge when row covers are used for control of soil erosion.

For an overall evaluation of this strategy, the **economic aspect** should be taken into consideration. The costs for insect nets are significantly higher than the costs for fleece cover, with the costs for a standard used insect net amounting to 6000 € $ha^{-1}$ while fleece costs an average of 1300 € $ha^{-1}$ (Table 2). However, the durability of nets is around six times higher than the fleece covers. Generally, time consuming covering and removing of the agrotextiles by hand should be considered and taken into account.

**Table 2:** Acquisition costs, working hours and durability of insect nets and fleece cover (KTBL, 2013).

| | **Acquisition costs $ha^{-1}$** | **Working hours (Wh) $ha^{-1}$** | **Durability** |
|---|---|---|---|
| **Insect net[1]** | 6000 € | Covering by hand:<br>7.90 Wh $ha^{-1}$ x 7.50 € $Wh^{-1}$=59.25 €<br>Removing by hand:<br>7.30 Wh $ha^{-1}$ x 7.50 € $Wh^{-1}$=54.75 € | 5-7 years |
| **Fleece[2]** | 1300 € | Covering by hand:<br>9.20 Wh $ha^{-1}$ x 7.50 € $Wh^{-1}$=69.00 €<br>Removing by hand:<br>8.60 Wh $ha^{-1}$ x 7.50 € $Wh^{-1}$=64.50 € | 1 year |

[1] Rantai K'; mesh size: 1.35 x 1.35 mm

[2] non-woven 17g-density fabric

### 7.1.2 Strip-tillage

White cabbage production under strip-tillage showed promising results related to soil erosion control and yield potential within this thesis (publication II and publication III). The results of significantly lower soil loss under strip-tillage in lettuce and white cabbage compared to conventional tillage are supported by findings of studies in cotton and on bare plots, which also find a significant reduction of water runoff and soil loss under strip-tillage (Truman et al., 2007; Strickland et al., 2012). The effects of strip-tillage on soil properties were clearly shown in this thesis through higher bulk density, higher penetration resistance and increased soil moisture content in the top soil under strip-tillage compared to conventional tillage (publication II). These results indicate only short-term effects on physical soil properties, but conservation tillage practices, such as strip-tillage, have to be performed over a longer time period in order to be fully effective. Several long-term studies showed that soil property effects are not manifested before 8 to 20 years after adoption of conservation tillage practices (Voorhees and Lindstrom, 1984; Hill and Cruse, 1985; Hussain et al., 1998).

The nitrogen dynamics can also be affected under conservation tillage (Wienhold and Halvorson, 1999). Hence, different tillage intensities and different N-fertilizer application techniques were tested under strip-tillage and conventional tillage (publication III). High nitrogen uptake rates and low soil mineral nitrogen contents at harvest time under the non-intensive, single tilled strip-tillage treatment including broadcast nitrogen fertilization indicate that cabbage plants are able to take up the nitrogen not only from the tilled area, but also from the untilled zone. Also, the highest cabbage head yields were achieved under non-intensive strip-tillage, compared to intensive strip-tillage or mouldboard ploughing. Therefore, there is no indication that double-tillage (autumn and spring) and band-placed nitrogen fertilization is needed for higher yield potential under strip-tillage. In general, the results demonstrate a high yield potential of white cabbage under strip-tillage, which is supported by the results of other studies in maize, sugar beet and also white cabbage (Licht and Al-Kaisi, 2005; Evans et al., 2010; Haramoto and Brainard, 2012).

As part of the project “Development of erosion control strategies for field grown vegetables”, **on-farm experiments** at the Filderebene were conducted in addition to field experiments at the research station to test the strip-tillage system under practical conditions. The results after three experimental years showed an average yield reduction of 15% under strip-tillage compared to conventional inversion-tillage (Table 3). High weed incidence at the on-farm fields (2011 and 2012) and wet weather conditions at the time of planting in 2013 may have caused the differences between the research station and the farmers’ fields.

**Table 3:** Fresh matter cabbage head yield at the on-farm experiments at the Filderebene (Übelhör et al., 2013).

| | Average fresh matter cabbage head yield (t ha$^{-1}$) | | |
|---|---|---|---|
| **Year** | **Mouldboard ploughing** | **Strip-tillage** | **Yield reduction under strip-tillage** |
| **2011** | 119 | 97 | 18% |
| **2012** | 100 | 88 | 12% |
| **2013** | 87 | 75 | 14% |

The production under strip-tillage under on-farm conditions demonstrates that there are still **limitations and challenges** associated with strip-tillage in vegetable production. Despite the use of non-selective herbicide in autumn and spring under strip-tillage, the **weed pressure** can be very high because mechanical weed control, e.g. with hoe is counterproductive to the goal of erosion control. The herbicide application rates can be even higher than under conventional tillage. Investigations in cotton also showed higher weed incidence under strip-tillage than under conventional tillage (Wiatrak et al., 2005) and weeds were only controlled by non-selective herbicide in addition to post-emergence herbicide application (Hayes et al., 1996). To control the weeds in strip-tillage or other conservation tillage systems, cover crops can be used in combination with a ‘roller-crimper’. This implementation represents a promising system, which could also improve the strip-tillage system for vegetables. The cover crop is “rolled down” by the machine, and afterwards strips can be prepared as usual. The cover crop mulch suppresses the weeds and simultaneously serves as soil protection and increases soil moisture. A weed suppression of 85% can be achieved by the roller-crimper system (Curren et al., 2011; Luna et al., 2012,).

Another challenge of strip-tillage is the **integration of vegetable crop rotations**. A typical crop rotation in southwest Germany is winter wheat - lettuce - cabbage. Within this rotation, strip-tillage is only possible if lettuce is also grown under strip-tillage. However, lettuce cultivation under strip-tillage is more difficult than cabbage (publication II) because of a higher demand on finely structured soil to achieve a high yield. Furthermore, the row spacing of lettuce is usually smaller than provided by strip-tillage, resulting in yield reduction due to the lower plant density. However, yield deficits caused by, for example wider row distances, can be compensated through savings in **fuel and labor requirements**. A comparison of costs between conventional tillage (mouldboard plough) and strip-tillage shows a cost reduction for fuel and working hours by nearly 50% (Table 4); however, lower production costs under strip-tillage are linked to high acquisition costs for new machinery. Strip-tillage machines are currently available from many manufacturers, with the price ranging from 25,000 € up to 50,000 € for the strip-tillage machine itself, plus approximately 20,000 € for the GPS-RTK guidance system.

**Table 4:** Cost comparison between conventional tillage and strip-tillage (modified according to Hermann, 2012 and KTBL, 2012). Representative example for heavy soils (>10% clay). Costs are variable between location and crop.

| | **Mouldboard ploughing** | | | **Strip-tillage** | | |
|---|---|---|---|---|---|---|
| **Operation** | Working hours (ha$^{-1}$)[4] | Fuel (L ha$^{-1}$)[5] | **€ ha$^{-1}$** | Working hours (ha$^{-1}$)[4] | Fuel (L ha$^{-1}$)[5] | **€ ha$^{-1}$** |
| **1.Stubble tillage** [1] | 0.55 | 9 | **40** | - | - | **-** |
| **2.Stubble tillage**[1] | 0.55 | 9 | **40** | - | - | **-** |
| **Strip-tillage, autumn**[2] | - | - | - | 0.23 | 2 | **32** |
| **Non-selective herbicide application, autumn** | - | - | - | 0.75 | 18 | **76** |
| **Primary tillage**[3] | 1.87 | 26 | **109** | - | - | **-** |
| **Non-selective herbicide application, spring** | - | - | - | 0.23 | 2 | **44** |
| **Strip-tillage, spring**[2] | - | - | - | - | - | **-** |
| **Seedbed preparation** | 0.57 | 9 | **39** | - | - | **-** |
| **Rotary harrow** | 0.97 | 17 | **68** | - | - | **-** |
| **Total** | **4.51** | **70** | **296** | **1.21** | **22** | **152** |

[1] shallow tillage with chisel plough

[2] costs of RTK-guidance system: 12 € ha$^{-1}$ (tillage area: 500 ha)

[3] mouldboard plough, 25 cm deep

[4] labor costs: 15 € h$^{-1}$

[5] price of fuel: 1.00 €

### 7.1.3 Feasibility, implementation and farmers' acceptance

Several factors have to be considered before recommendations can be given to farmers (Table 5). In general, both row covers and strip-tillage seem to be promising approaches for minimizing soil erosion in vegetable production. Soil erosion control under both strategies can be assessed as high. Essentially, the productivity under row covers and strip-tillage systems is also high, but there are several factors, which can severely affect the yield. For row covers, these are (i) increased risk of plant diseases, particularly under wet and warm weather conditions and (ii) increased weed infestation under row covers, with the same factors applying to strip-tillage. Weed control is a big challenge for the future and strategies must be developed to minimize this problem. Vegetable growers are dependent on effective weed control strategies because of the limited number of authorised herbicides and consideration of long pre-harvest intervals. Another limiting factor is the strip quality and the soil conditions at planting date. The soil must be dry at strip preparation in autumn and transplanting in spring, otherwise the strips become very cloddy and root-soil contact is poor.

From an economic point of view, row covers seem more attractive for farmers than the high costs of the strip-tillage equipment. In this context, the field and farm size are the determining factors. The implementation of conservation tillage practices, such as strip-tillage on German farms, will be long and difficult. The main reason can be found in the small farm sizes, which are particularly prevalent in the south of Germany. The average farm size in Baden-Wuerttemberg is 32 ha, and the average size of vegetable producing farms is only 8 ha (BMBL, 2014). It is obvious that tillage systems such as strip-tillage are only suitable and profitable if farmers join together to acquire machines. Besides financial aspects of new equipment, there are several concerns regarding whether profits under strip-tillage are similar to those under conventional tillage. The only solution to increase the acceptance of farmers and to implement strip-tillage in the farming practice is probably to subsidise the technique as part of agri-environmental programs such as MEKA (Marktentlastung und Kulturausgleich) in Baden-Wuerttemberg. For the next generation of agri-environmental programs, namely FAKT, strip-tillage is implemented in the preliminary draft as a support measure for application in maize, sugar beet and field grown vegetables (MLR, 2014).

In the current study, white cabbage was used as a model crop to develop and investigate the erosion control strategies. The question arises whether the results can be transferred and adapted to other field grown vegetables. In particular, the erosion risk in lettuce cultivation is still higher than that of cabbage due to the sparsely covered soil surface during the entire cultivation period. Preliminary results of lettuce cultivation under strip-tillage, which are partly included in publication II, showed, in general, an acceptable yield potential. Due to the wide row distances under strip-tillage, however the system is currently not a feasible option for farmers. In lettuce, cultivation fleece is commonly used as frost protection is fairly suitable as an erosion control measure. Because plant diseases are triggered by the increased temperatures and humidity under fleece, and because lettuce is particularly susceptible to rot pathogens, fleece as an erosion control measure in lettuce can only be recommended to a limited extent. Other *Brassica* varieties, such as broccoli (*Brassica oleracea* var. *italica* Plenck), Brussel sprouts (*Brassica oleracea* var. *gemmifera*), or cauliflower (*Brassica oleracea* var. *botrytis* L.) probably be easily grown under the two strategies.

In summary, based on the results of this study, row covers can be recommended from an agronomic and economic point of view for temperate climate zones as an erosion control strategy. Small fields seem particularly suitable and for short-term use on specific erosion-prone fields. On a large-scale, strip-tillage seems to be better suited as a sustainable, long-term strategy to protect soil against erosion and degradation. Although it is difficult to change and adopt vegetable crop rotations completely to conservation tillage, strip-tillage could be a valuable option in a multi-year crop rotation towards reducing soil erosion in erosion-prone crops.

**Table 5:** Evaluation of row covers (fleece and net cover) and strip-tillage for white cabbage production according to erosion control, productivity (yield potential), economy, farmers' acceptance and applicability to other vegetables. +: low; + +: medium; + + +: high

| | Erosion control | Productivity | Economy | Farmers' acceptance | Applicability to other vegetables |
|---|---|---|---|---|---|
| **Fleece cover** | + + + | + + | + + + | + + + | + + |
| **Net cover** | + + | + + | + + | + + | + + |
| **Strip-tillage** | + + + | + + + | + | + | + + |

## 7.2 Plant growth simulation of vegetables

In publication IV of this thesis, the process-oriented plant growth simulation model CROPGRO was evaluated for cabbage production under temperate European climate conditions. The results indicate that the model is a suitable tool to simulate cabbage yield potentials for temperate climates. Furthermore, the sensitivity analysis for different nitrogen fertilization rates and different fertilizer application strategies generated logical and reasonable results. In spite of these promising results and supporting findings from other simulation studies conducted in Chinese cabbage (Feike, 2010) and tomato (Scholberg et al., 1997), process-oriented modeling approaches for field grown vegetables are still relatively rare. The existing modeling approaches for vegetables are restricted to descriptive models, which have been available for quite some time. These models are based on mathematical functions to describe crop growth, development rate and yield, often depending on environmental factors, such as temperature or light intensity (Liebig, 1980; Fisher et al., 1996; Lieth et al., 1996). They are adequate to calculate harvest dates or yields, which can be important for production planning. However, the adaption and extrapolation of descriptive models to other crop species or other locations is often impossible because the model input factors (e.g. temperature) can change the growing process, making the initially used mathematical function for yield prediction or harvest time modeling invalid (Marcelis et al., 1998). In contrast to descriptive model approaches, process-oriented models, such as DSSAT CROPGRO, integrate several factors which influence plant growth significantly. This includes the calculation of carbon, nitrogen or water balances during the growing season which affect yield and dry matter accumulation (Boote et al., 2003). These models are therefore able to describe generative and reproductive plant development and growth under different climate and soil conditions. In addition to high yields, the product quality of vegetables plays an important role. Hence, the implementation of a tool which can predict parameters of product quality could improve plant growth models for vegetables enormously. If the model would be able to simulate quality parameters, such as core length and head strength of cabbage or to estimate quality compounds, such as Vitamin C or glucosinulate concentration, under different crop management strategies, the field of application could be increased in the future.

To increase the perspectives of crop growth modeling for vegetables, it is necessary to adapt the models, which were originally developed for arable crops, such as maize or legumes, to the specific requirements of vegetables. Hence, data set volume for model calibration and validation for different cultivars and for further climate conditions should be increased before the model results can be used for decision support or recommendations for farmers.

## 7.3 Outlook

Soil erosion caused by water will be challenging for future crop production. According to predictions, summer rainfall events will decrease by 30% while the frequency of extreme weather and heavy rainfall events will increase significantly in Germany (Schulz, 2013). This could lead to an increase in coming centuries in the risk of on-site and off-site damages by water erosion. Furthermore, model simulations predict higher temperatures accompanied by a higher atmospheric $CO_2$ concentration (Trenberth et al., 2003; IPCC, 2007). This could lead to land-use changes, in terms of an extended length of the growing season and the implementation of new crops in new areas. Consequences could include an intensified risk of soil erosion due to altered sowing, planting and harvesting dates, including changes in tillage practices, which can affect soil properties and soil erodibility. The current and future damages by soil erosion in agriculture require changes in regulation of the federal soil protection act or in the Cross Compliance regulations. Hence, in the future, soil conservation must focus even more on intensive crop production and farmers, particularly vegetables growers, will be increasingly dependent on erosion control strategies. For this reason, the approaches as presented and discussed in this thesis (row covers and strip-tillage) can contribute significantly to produce field grown vegetables in a sustainable way that promotes soil protection.

# 8 Summary

Soil erosion by wind and water is a widely recognized problem throughout the world. In Europe, 16% of the total land area is affected by water erosion. Field grown vegetables, such as white cabbage (*Brassica oleracea* convar. *capitata* var. *alba* L.), are particularly endangered by soil erosion because of high disturbance tillage, including deep inversion tillage by the mouldboard plough. Furthermore, wide row spacing and late soil covering by leaves intensify the problem. In light of this, field experiments were conducted from 2011 to 2013 in southwest Germany to investigate, develop and adapt soil erosion control strategies, in particular for field grown vegetables, with white cabbage as a model crop. Focus was placed first, on the use of row covers (fleece and nets), which are usually used as frost protection or for pest control in organic farming, and second, on the development and adoption of strip-tillage for field grown vegetables, which combine the benefits from conventional tillage (high yields) and no-tillage (erosion control).

Artificial rainfall simulations were carried out in 2012 at the experimental station ‘Hohenheim gardens’ of the University of Hohenheim to assess the effect of row covers on soil loss and water runoff. In 2012 and 2013 the influence of row covers on white cabbage growth was investigated at the experimental station ‘Ihinger Hof’. Continuous measurements of soil and air temperature, relative humidity and soil moisture content were conducted to describe the microclimate under fleece and net cover. Plant samples were taken, the infestation with pests and diseases on cabbage plants were assessed in regular intervals and finally, cabbage yield was determined.

To develop and investigate the strip-tillage system for vegetable crops, field experiments were conducted from 2011 to 2013 at ‘Ihinger Hof’. Erosion control of strip-tillage compared to conventional tillage was investigated in lettuce (*Lactuca sativa* var. *capitata* L.; 2011) and white cabbage (2012) through artificial rainfall simulations. Bulk density, penetration resistance and moisture content were measured under strip-tillage and conventional tillage. Nitrogen dynamics in soil (soil mineral nitrogen) and in white cabbage plants (total nitrogen content, N-uptake, nitrogen use efficiency) were investigated under different tillage intensities and different nitrogen application techniques in strip-tillage compared to conventional tillage. Here, non-intensive strip-tillage with only strip preparation in autumn and broadcast nitrogen fertilization was compared to the intensive strip-tillage, with strip preparation in autumn and spring with either broadcast or band-placed nitrogen fertilization. Finally, cabbage yield was determined in each year.

In addition, data sets from the field experiments were used to evaluate the process-oriented crop growth simulation model DSSAT CROPGRO for white cabbage production under temperate, European climate conditions.

The following hypotheses were examined within the study:

(1) Row covers, such as fleece and nets, can serve as an erosion control strategy, but the risk of plant diseases is increased by the modified microclimate under row covers.

(2) Soil erosion is reduced under strip-tillage compared to conventional tillage.
(3) Bulk density, penetration resistance and soil moisture content are higher under strip-tillage than under conventional tillage.
(4) Cabbage yield potential is lower under non-intensive strip-tillage (strip preparation in autumn) than under intensive strip-tillage (strip preparation in autumn and spring) and conventional tillage.
(5) Band-placed nitrogen fertilization under strip-tillage leads to higher nitrogen availability and to higher yields compared to broadcast fertilization.
(6) The crop growth simulation model CROPGRO is suitable for predicting cabbage yields under temperate European climate.

Artificial rainfall simulations demonstrated a high erosion control by row covers. Soil loss under fleece cover was reduced on average by 76% and under net cover by 48% compared to the uncovered control treatment. Soil temperature did not differ significantly between the treatments. Soil moisture content, air temperature and relative humidity were measured in the order of fleece cover > net cover > uncovered control. In 2012, fresh matter head yield was significantly higher under fleece (80 t ha$^{-1}$) than control treatment (66 t ha$^{1}$). The opposite was found in 2013, with highest yield under the non-covered control (64 t ha$^{-1}$) and lowest under fleece cover (53 t ha$^{-1}$). A higher prevalence of diseases under row covers compared to the control was only found in 2012 with *Sclerotinia sclerotiorum* on 4% of cabbage heads under fleece cover.

Soil loss under strip-tillage during artificial rainfall simulations in 2011 was reduced by an average of 80% compared to conventional tillage (512 g m$^{-2}$). In 2012, soil losses were reduced by an average of 90% under non-intensive strip-tillage and by 48% under intensive strip-tillage compared to conventional tillage (210 g m$^{-2}$). Bulk density, penetration resistance and soil moisture content decreased in top soil (0-10 cm) in the order of no-tilled zone of strip-tillage > conventional tillage > tilled zone of strip-tillage. No significant differences in soil mineral nitrogen from 0-90 cm soil depth were detected in spring (20 ±5 kg N ha$^{-1}$) or at harvest time (5 ±0.9 kg N ha$^{-1}$) between conventional tillage and strip-tillage treatments in each experimental year. During the growing period, soil mineral nitrogen contents in strip-tillage treatments tended to be higher than under conventional tillage. Nitrogen contents in plants, N-uptake and nitrogen use efficiency showed higher values under the non-intensive strip-tillage treatment than under conventional tillage and under intensive strip-tillage treatments with broadcast or band-placed nitrogen fertilization. The fresh matter head yield in 2011 and 2013 under strip-tillage (58 t ha$^{-1}$ and 57 t ha$^{-1}$, respectively) was similar to conventional tillage (59 t ha$^{-1}$ and 58 t ha$^{-1}$, respectively). In 2012, cabbage yield was significantly higher under strip-tillage (74 t ha$^{-1}$) than under conventional tillage (65 t ha$^{-1}$). The intensive strip-tillage treatments with broadcast and band-placed nitrogen fertilization did not show a yield increase. Yield potential under band-placed fertilized strip-tillage was, at 67 t ha$^{-1}$ (2012) and 50 t ha$^{-1}$ (2013), the lowest within the strip-tillage treatments.

The CROPGRO cabbage model was evaluated for cabbage production under temperate European climate conditions. After calibration of main parameters of phenology and plant growth, the model showed a high accuracy with indices of agreement mostly above d=0.94. Observed dry matter cabbage head yields of the different years and different locations ranged between 6574 kg ha$^{-1}$ and 11926 kg ha$^{-1}$ which were predicted by the model with an accuracy of $R^2$=0.98. Also the sensitivity analysis, conducted under different nitrogen fertilizer amounts and different fertilizer application strategies, generated realistic values from an agronomic point of view.

Overall, row covers and strip-tillage seem to be suitable for minimizing the erosion risk in vegetable production. The hypotheses of high erosion control under row covers and strip-tillage can be accepted. Due to the modified microclimate under row covers, the infestation with pests and diseases can increase and the influence on cabbage growth can result in either a yield increase or decrease. Based on the study results, there is no evidence that the intensive, double-tilled strip-tillage treatment or the band-placed nitrogen fertilization lead to a yield increase. The non-intensive strip-tillage with only soil preparation in autumn showed the highest yield potential within the strip-tillage treatments, with similar or even higher yields than under conventional tillage. Furthermore, the CROPGRO cabbage model is suitable to simulate growth parameters and yield potential of white cabbage under temperate European climate conditions. For the future, due to the prediction of increased frequency of heavy rainfall events, soil conservation will focus increasingly on intensive crop production and farmers, particularly vegetables growers, will be increasingly dependent on erosion control strategies. For this reason, the approaches presented in this thesis can contribute significantly to produce field grown vegetables in a sustainable way that promotes soil protection.

# 9 Zusammenfassung

Bodenerosion, ausgelöst durch Wind und Wasser, ist ein weltweites Problem. In Europa sind 16% der gesamten Landfläche von Wassererosion betroffen. Vor allen Dingen Feldgemüse, wie zum Beispiel Weißkohl (*Brassica oleracea* convar. *capitata* var. *alba* L.), ist durch eine intensive Bodenbearbeitung einem besonders hohen Erosionsrisiko ausgesetzt. Weite Reihenabstände und ein später Reihenschluss verstärken das Problem zusätzlich. Aus diesem Grund wurden in den Jahren 2011 bis 2013 in Südwestdeutschland Feldversuche durchgeführt, um ausgewählte Erosionsschutzmaßnahmen im Feldgemüsebau zu untersuchen, zu entwickeln und anzupassen. Hierbei standen zwei Maßnahmen im Fokus. Erstens wurde eine Abdeckung der Flächen mit Vlies und Kulturschutznetz als Erosionsschutz getestet, die derzeit vor allem als Frostschutz- bzw. als Pflanzenschutzmaßnahme im ökologischen Landbau eingesetzt werden. Zweitens wurde das Strip-Tillage Verfahren für den Feldgemüsebau angepasst, bei dem die Vorteile der konventionellen mit denen der konservierenden Bodenbearbeitung verbunden werden sollen.

Zur Prüfung der Bodenbedeckung durch Textilien auf Bodenabtrag und Wasserabfluss wurden im Jahr 2012 Beregnungsversuche auf der Versuchsstation der Universität Hohenheim „Hohenheimer Gärten“ durchgeführt. 2012 und 2013 wurde auf der Versuchsstation Agrarwissenschaften, Standort Ihinger Hof, der Einfluss von Vlies und Kulturschutznetz auf das Weißkohlwachstum untersucht, wobei kontinuierliche Messungen von Boden- und Lufttemperatur sowie von Boden- und Luftfeuchtigkeit durchgeführt wurden, um Veränderungen des Mikroklimas unter den Textilien zu dokumentieren. Darüber hinaus wurden über die Kulturdauer hinweg Zeiternten durchgeführt, das Auftreten von Krankheitssymptomen bonitiert und abschließend der Weißkohlertrag bestimmt.

Zur Entwicklung und Anpassung des Strip-Tillage Verfahrens für Feldgemüsekulturen wurden von 2011 bis 2013 Feldversuche auf der Versuchsstation Ihinger Hof durchgeführt. Hierbei wurde in Beregnungsversuchen der Bodenabtrag beim Anbau von Kopfsalat (*Lactuca sativa* var. *capitata* L.; 2011) und von Weißkohl (2012) im Strip-Tillage Verfahren und bei konventioneller, wendender Bodenbearbeitung mit dem Pflug bestimmt. Des Weiteren wurde die Lagerungsdichte, der Eindringwiderstand und die Wassergehalte im Strip-Tillage Verfahren und bei konventioneller Bodenbearbeitung gemessen. Die Stickstoffdynamik im Boden und in der Pflanze wurde durch die regelmäßige Entnahme von Boden- und Pflanzenproben über die komplette Kulturdauer hinweg untersucht. Beim Strip-Tillage Verfahren wurde in eine nicht-intensive Variante mit einmaliger Streifenbearbeitung im Herbst und breitwürfiger Stickstoffdüngung, und in eine intensive Variante mit doppelter Streifenbearbeitung (im Herbst und im Frühjahr) mit breitwürfiger als auch mit platzierter Stickstoffdüngung unterschieden. Im Herbst erfolgte schließlich in jedem Versuchsjahr eine Ertragsbestimmung.

Drittens wurde auf Basis der in den Feldversuchen erhobenen Daten das prozessorientierte Pflanzenwachstumsmodell DSSAT CROPGRO für den

Weißkohlanbau unter gemäßigten, europäischen Klimabedingungen kalibriert und validiert.

In der vorliegenden Arbeit wurden folgende Hypothesen aufgestellt und geprüft:

(1) Vlies- und Netzabdeckungen dienen als Erosionsschutz, allerdings steigt das Krankheitsrisiko durch das veränderte Mikroklima unter den Abdeckungen.

(2) Die Bodenerosion wird durch das Strip-Tillage Verfahren im Vergleich zur konventionellen Bodenbearbeitung reduziert.

(3) Lagerungsdichte, Eindringwiderstand und Bodenwassergehalte sind im Strip-Tillage Verfahren höher als bei konventioneller Bodenbearbeitung.

(4) Die Weißkohlerträge sind bei der nicht-intensiven Strip-Tillage Variante (Streifenbearbeitung ausschließlich im Herbst) niedriger als bei der intensiven Strip-Tillage Variante (Streifenbearbeitung im Herbst und Frühjahr) und bei konventioneller Bodenbearbeitung.

(5) Eine platzierte Stickstoffdüngung beim Strip-Tillage Verfahren führt zu einer höheren Stickstoffverfügbarkeit und zu höheren Erträgen als eine breitwürfige Düngung.

(6) Mit dem Pflanzenwachstumsmodell CROPGRO kann das Weißkohlertragspotential unter gemäßigten europäischen Klimabedingungen abgeschätzt werden.

Innerhalb den Beregnungsversuchen konnte ein hoher Erosionsschutz durch die Abdeckungen nachgewiesen werden. Der Bodenabtrag war im Vergleich zur unbedeckten Kontrolle unter Vlies im Mittel um 76% reduziert und beim Kulturschutznetz um 48%. Die Bodentemperaturen unterschieden sich nicht signifikant zwischen den unterschiedlichen Varianten. Die Höhe der Lufttemperatur sowie die Luft- und Bodenfeuchtigkeit sank in der Reihenfolge Vlies > Kulturschutznetz > unbedeckte Kontrolle. Der Kopfertrag von Weißkohl (Frischmasse) war im Jahr 2012 unter der Vliesabdeckung mit 80 t $ha^{-1}$ signifikant höher als in der unbedeckten Kontrolle mit 66 t $ha^{-1}$. Das gegenteilige Ergebnis fand sich im Jahr 2013 mit höheren Kopferträgen in der unbedeckten Kontrolle (64 t $ha^{-1}$) gegenüber denen unter Vlies (53 t $ha^{-1}$). Offensichtliche Krankheiten traten nur in 2012 auf. Hier wiesen 4% der Weißkohlköpfe, die mit Vlies bedeckt waren, Symptome von *Sclerotinia sclerotiorum* auf.

Der Bodenabtrag im Strip-Tillage Verfahren war bei den Beregnungsversuchen im Jahr 2011 um 80% geringer als bei der konventionellen Bodenbearbeitung (512 g $m^{-2}$). In 2012 waren die Abträge in der nicht-intensiven Strip-Tillage Variante um 90% geringer und in der intensiven Strip-Tillage Variante um 48% geringer gegenüber der konventionellen Bodenbearbeitung (210 g $m^{-2}$). Die Lagerungsdichte, der Eindringwiderstand und die Bodenwassergehalte nahmen im Jahr 2011 im Oberboden (0-10 cm) in folgender Reihenfolge ab: nicht bearbeiteter Bereich im Strip-Tillage Verfahren > konventionelle Bodenbearbeitung > bearbeiteter Bereich im Strip-Tillage Verfahren. Die $N_{min}$-Gehalte im Boden (0-90 cm) zeigten weder im Frühjahr (20 ± 5 kg N $ha^{-1}$) noch zur Ernte im Herbst (5 ± 0.9 kg N $ha^{-1}$) in den beiden Versuchsjahren signifikante Unterschiede zwischen konventioneller

Bodenbearbeitung und Strip-Tillage. Insgesamt waren jedoch während der Vegetationszeit die $N_{min}$-Gehalte im Strip-Tillage Verfahren tendenziell höher als bei konventioneller Bodenbearbeitung. Die Stickstoffgehalte der Pflanzen, die Stickstoffaufnahmeraten und die Stickstoffausnutzungseffizienz waren bei der nicht-intensiven Strip-Tillage Variante höher als bei konventioneller Bodenbearbeitung und als in den intensiven Strip-Tillage Varianten. In den Jahren 2011 und 2013 wurden im Strip-Tillage Verfahren mit 58 t $ha^{-1}$ bzw. 57 t $ha^{-1}$ nahezu gleich hohe Weißkohlerträge wie bei konventioneller Bodenbearbeitung (59 t $ha^{-1}$ bzw. 58 t $ha^{-1}$) erreicht. 2012 konnte mit 74 t $ha^{-1}$ im Strip-Tillage Verfahren sogar ein signifikant höherer Kopfertrag als bei konventioneller Bodenbearbeitung (65 t $ha^{-1}$) erzielt werden. Die intensiven Strip-Tillage Varianten zeigten weder unter breitwürfiger noch platzierter Stickstoffdüngung eine Ertragssteigerung gegenüber der nicht intensiven Strip-Tillage Variante. Die platziert gedüngte Variante wies mit 67 t $ha^{-1}$ (2012) und 50 t $ha^{-1}$ (2013) jeweils die niedrigsten Kopferträge innerhalb den getesteten Strip-Tillage Verfahren auf.

Das CROPGRO-Modell wurde für den Weißkohlanbau unter gemäßigten, europäischen Klimabedingungen zunächst kalibriert und dann validiert. Nach der Kalibrierung der Modellfaktoren, die die Phänologie und das Pflanzenwachstum hauptsächlich beeinflussen, konnte eine sehr hohe Modellgenauigkeit erreicht werden (Index of Agreement > 0.94). Die gemessenen Kopferträge des Weißkohls (Trockenmasse) an den verschiedenen Standorten und den verschiedenen Jahren lagen zwischen 6.574 kg $ha^{-1}$ und 11.926 kg $ha^{-1}$. Die Simulation dieser großen Ertragsspanne wies ebenfalls eine sehr hohe Modellgenauigkeit mit $R^2$=0.98 auf. Auch die Sensitivitätsanalyse, die mit verschiedenen Stickstoffdüngermengen und verschiedenen Applikationsstrategien durchgeführt wurde, ergab aus agronomischer Sicht plausible Werte.

Zusammenfassend stellen sowohl die Abdeckungen (Vlies und Kulturschutznetz) als auch das Strip-Tillage Verfahren geeignete Erosionsschutzmaßnahmen für den Feldgemüsebau, hier am Beispiel Weißkohl, dar. Die Hypothese, dass Vlies und Kulturschutznetz sowie das Strip-Tillage Verfahren einen hohen Schutz vor Wassererosion bieten, wird angenommen. Durch das veränderte Mikroklima unter den Abdeckungen kann jedoch ein erhöhter Krankheitsdruck auftreten und das Pflanzenwachstum kann sowohl günstig als auch ungünstig beeinflusst werden. Beim Einsatz von Vlies und Kulturschutznetz sollten daher die jährlich schwankenden Wetterbedingungen beachtet werden.

Ausgehend von den Ergebnissen dieser Studie gibt es derzeit keinen Hinweis, dass durch eine intensive, mehrmalige Streifenbearbeitung und durch eine platzierte Stickstoffdüngung der Ertrag im Strip-Tillage Verfahren gesteigert werden kann. Vielmehr zeigte das nicht-intensive Strip-Tillage Verfahren, mit einmaliger Streifenbearbeitung im Herbst, das höchste Ertragspotential innerhalb der getesteten Strip-Tillage Varianten mit vergleichbaren oder sogar höheren Erträgen als bei konventionellen Bodenbearbeitung. Das Pflanzenwachstumsmodell CROPGRO ist in der Lage, Wachstumsparameter und Ertragspotentiale im Weißkohl unter gemäßigten, europäischen Klimabedingungen zu simulieren.

Grundsätzlich könnten sowohl Vlies- und Kulturschutznetzabdeckungen als auch das Strip-Tillage Verfahren als Erosionsschutzmaßnahmen für den Feldgemüsebau unter gemäßigten Klimabedingungen eingesetzt werden. Durch die vorhergesagte, steigende Anzahl an Starkregenereignissen wird der Bodenschutz zukünftig noch mehr in den Fokus der Landwirtschaft rücken. Landwirte, und insbesondere Gemüseproduzenten werden immer mehr auf Erosionsschutzmaßnahmen angewiesen sein, wodurch mit den vorgestellten Ansätzen ein wesentlicher Beitrag zum nachhaltigen und bodenschonenden Feldgemüsebau geleistet werden kann.

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# Appendix

**Table A6:** General overview over presentations and publications in context of the dissertation.

**A. Übelhör**, J. Pfenning, W. Hermann, N. Billen, J. Morhard, W. Claupein, H.-P. Liebig: Conservation Tillage in Intensive Vegetable Production Systems-Strip Tillage in White Cabbage Cultivation; *Poster presentation*: 2nd Symposium on Horticulture in Europe, 1-5 July 2012, Angers, France

**A. Übelhör**, J. Pfenning, W. Hermann, N. Billen, J. Morhard, W. Claupein: Erosionsschutz im Feldgemüsebau: Etablierung des Strip-tillage Verfahrens bei Weißkohl; *Conference proceeding and poster presentation:* Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften, Bd. 24; 55. Tagung der GPW,
24-27 September 2012 in Berlin, pp.202-203

**A. Übelhör**, N. Billen, W. Hermann, J. Morhard, W. Claupein: Strip-tillage im Feldgemüsebau -Schutz vor Erosion und Austrocknung-; *Oral presentation*: Internationale wissenschaftliche Konferenz: Nährstoff- und Wasserversorgung der Pflanzenbestände unter den Bedingungen der Klimaerwärmung,
18-19 October 2012, Bernburg-Strenzfeld

**A. Übelhör**, N. Billen, W. Hermann, J. Morhard, J. Pfenning, K. Köller, W. Claupein: Strip-Till im Weißkohlanbau – Wirksamer Erosionsschutz im Gemüsebau; *Non peer-reviewed publication:* Kohl - Aktuelle Versuchsergebnisse und Informationen aus Baden-Württemberg 2013, LVG Heidelberg (Eds.)

**A. Übelhör**, N. Billen, J. Morhard, W. Hermann, W. Claupein: Bodenerosion im Feldgemüsebau –Lösungsansätze in Baden-Württemberg – *Conference proceeding and oral presentation*: BHGL – Schriftenreihe Band 29, 48. Gartenbauwissenschaftliche Tagung, 27 February-2 March 2013, Bonn, p. 27

**A. Übelhör**, W. Claupein, W. Hermann, J. Morhard, N. Billen: Ist Strip-Tillage eine Alternative zum Pflügen? Weißkohl in Streifen gepflanzt; *Non peer-reviewed publication:* LOP Landwirtschaft ohne Pflug; 5/2013, pp. 24-29

**A. Übelhör**, N. Billen, H. Ziegenhagel, S. Gruber und W. Claupein: Strip-Till im Weißkohlanbau – Wasserhaushalt und N-Düngestrategie- *Conference proceeding and poster presentation:* Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften, Bd. 25, 56. Tagung der GPW, 4-6 September 2013,Weihenstephan, pp. 313-314

**A. Übelhör**, M. Schlayer, L. Sauer, A. Stein, S. Zikeli, Claupein W.: Soil erosion in vegetable production – Solution approaches - *Conference proceeding and oral presentation*: NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality. 16-18 September 2013, Ghent, Belgium; pp. 43-48

**A. Übelhör**: Entwicklung erosionsmindernder Anbauverfahren im Feldgemüsebau; *Oral presentation:* Gemüsebautag Südwest, 18 February 2014, Oedheim

**A. Übelhör**, H. Sauer, K. Rather: Ansätze für den vorbeugenden Erosionsschutz im Gemüsebau am Beispiel von Weißkohl; Arbeitshilfe für die Umweltgerechte Landbewirtschaftung, Eds.: LVG Heidelberg (Eds.) February 2014

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# Eidesstattliche Erklärung

Hiermit bestätige ich, dass ich die vorliegende Dissertation selbst und nur unter Verwendung der angegebenen Quellen und Hilfsmittel angefertigt habe. Wörtlich oder inhaltlich übernommene Stellen sind als solche gekennzeichnet. Die Hilfe einer kommerziellen Promotionsvermittlung oder -beratung wurde nicht in Anspruch genommen.
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Hohenheim, Juli 2014 Annegret Übelhör