Organic Farming | 2016 | Volume 2 | Issue 1 | Pages 1–16
DOI: 10.12924/of2016.02010001
ISSN: 2297–6485

Research Article

# Management Options for Organic Winter Wheat Production under Climate Change

Ralf Bloch[1,2,*], Jürgen Heß[3] and Johann Bachinger[1]

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Institute of Land Use Systems, Müncheberg, Germany
[2] Eberswalde University for Sustainable Development, University of Applied Sciences, Eberswalde, Germany
[3] University of Kassel, Witzenhausen, Department of Organic Farming and Cropping Systems, Witzenhausen, Germany

* Corresponding author: E-Mail: bloch@zalf.de; Tel.: +49 3343282423; Fax: +49 3343282387

Submitted: 25 September 2015 | In revised form: 16 March 2016 | Accepted: 19 March 2016 | Published: 19 April 2016

**Abstract:** An effective adaptive strategy for reducing climate change risks and increasing agro-system resiliency is broadening cropping system diversity, heightening the flexibility of cultivation and tillage methods. Climate change impacts on standard cultivation practices such as mineralisation and nitrate leaching due to mild and rainy winters, as well as frequent drought or water saturation, not only limiting fieldwork days, but also restricting ploughing. This calls for alternative methods to counteract these propensities. From 2010 to 2013, a farming system experiment was conducted on a distinctly heterogeneous organic farm in Brandenburg, Germany. With the intention of devising a more varied and flexible winter wheat cultivation method, standard organic farming practices (winter wheat cultivation after two years of alfalfa-clover-grass and ploughing in mid-October) were compared to four alternative test methods, which were then evaluated for their robustness and suitability as adaptive strategies. Two of the alternative methods, *early sowing* and *catch crop*, entailed moving up the date for alfalfa-clover-grass tilling to July. Instead of a plough, a ring-cutter was used to shallowly (8 cm) cut through and mix the topsoil. In the *early sowing* test method, winter wheat was sown at the end of August, after repeated ring-cutter processing. With the *catch crop* method, winter wheat seeding followed a summer catch crop and October tillage. The two oat methods (*oat/plough*; *oat/ring-cutter*) entailed sowing winter wheat in September, following oat cultivation. Overall, the cultivation methods demonstrated the following robustness gradation: standard practice = *catch crop* ≥ *early sowing* > *oat/plough* > *oat/ring-cutter*. When compared to standard procedures, the catch crop and early sowing test methods showed no remarkable difference in grain yields. Measured against early sowing, the *catch crop* test method was significantly more robust when it came to winterkill, quality loss, and weed infestation (40% lower weed-cover). High $N_{min}$-values (up to 116 kg N $ha^{-1}$) in autumn could have caused the chamomile and thistle infestation in both *oat/plough* and *oat/ring-cutter* test methods, which led to crop failure in the hollows. Compared to standard practices, the *oat ring-cutter* test method brought in over 50% less grain yield. This was attributed to ring-cutter processing, which reduced N mineralisation and caused high weed infestation. However, the ring-cutter effectively regulated alfalfa-clover-grass fields in both exceedingly wet and very dry weather; a temporal flexibility which increases the number of fieldwork days. The *catch crop* and *early sowing* test methods contributed most to boosting future agronomic diversity.

**Keywords:** Adaptive capacity; cropping systems; on-farm research; reduced tillage; winter wheat

## 1. Introduction

Farmers today face the challenge of adapting their crop cultivation methods to climatic changes. In the near future, farms with a high adaptive capacity will have a distinct advantage. The adaptive capacity of a farm is established first and foremost by expanding diversity and flexibility [1]. Between 2009 and 2014, strategies to increase the adaptive capacity of organic farms were developed within the interdisciplinary project Innovation Network of Climate Change Adaptation Brandenburg Berlin (INKA BB; http://www.inka-bb.de/). Addressing practical issues regarding climate change adaptation, farmers and scientists worked together to develop modification measures, which were then tested on-site [2]. This paper illustrates a farming system experiment probing test methods for adapting winter wheat cultivation to climate change. The experiment was carried out from 2010 to 2013 in northeast Germany on the stockless organic farm Wilmersdorf.

### *1.1. Problem Description*

Winter wheat provides the economic foundation for the Wilmersdorf organic farm and has, thus far, been cultivated solely according to standard procedures. These standard organic farming procedures entail sowing winter wheat on fields prepared with a two-year multispecies legume-grass (LGS), which is mulched two to four times a year and ploughed under in autumn of the second harvest year. Directly following this virgin tillage (i.e. ploughing the sward without prior shallow soil processing), winter wheat is sown in mid-October. The subsequent crop is usually winter rye. This standard cultivation practice is practiced on large, rolling fields averaging 40 hectares, interspersed with *hills and hollows*. Such small-scale heterogeneity with varying soil types (see Section 2.2), further complicates ploughing and seedbed preparation. Poor soil contact and uneven germination are common problems. Particularly during dry periods, a common occurrence at Wilmersdorf (Section 2.3), hilltops are low yield (problem) areas and ploughing the shallow topsoil there is limited. In contrast, the hollows are often waterlogged, particularly in spring and in years with heavy precipitation, which also severely limits ploughing. The farm manager reports an annual fluctuation in winter wheat yields, between 0.9–5.8 t $ha^{-1}$ (Ø 3.5 t $ha^{-1}$). Therefore, to attain high winter wheat yields with the standard practice, the nitrogen (N) supply from LGS residuals and the N-up-take vital to winter wheat development must occur synchronously [3]. This process is closely linked to the water supply and the soil's microbial activity, which could be strongly influenced by climate changes projected for Brandenburg [4]. Such climatic developments include frequent mild and wet winters, increasing spring and summer droughts, recurrent extreme weather events (heavy rainfall and drought), and a rise in the average annual temperature [5]. Figure 1 depicts projected climatic changes from 2062 to 2092, illustrating their effects on the Wilmersdorf organic farm.

In view of these projected climate changes, the current standard cultivation practice reveals several weaknesses:

LGS virgin tilling in mid-October, followed by a mild and rainy winter, may lead to N-mineralisation, nitrate leaching and erosion, as the low development of winter wheat mass is unable to take up sufficient nitrogen at this time [6]. On the other hand, increasing drought in early spring reduces microbial nitrogen release [7]. This can result in an N-deficiency during developmental phases, when winter wheat has high nitrogen requirements (Stem elongation; Zadoks scale 30–32) [8]. Furthermore, ploughing in autumn heightens erosion susceptibility and the risk of plough sole compression [9]. As a result, root depth and infiltration can be retarded, hindering the soil's buffering capacity in extreme weather events (heavy rain and drought).

These issues are compounded by the influence dry periods and increased precipitation in late autumn and winter has on the *number of suitable fieldwork days* for ploughing and sowing. In the future, winter crop sowing conditions could deteriorate in direct proportion to the instability of appropriate fieldwork days [10].

Since LGS processes great quantities of water via transpiration, increasing temperatures can potentially lead to a water shortage in the soil, inhibiting subsequent crop growth [9]. Despite uncertainties in climate predictions, the above listed weaknesses illustrate how strongly climatic changes may influence growth, site and weather conditions, and so of course crop yields. The question is, which strategies and measures can minimise yield risk in future winter wheat cultivation on the Wilmersdorf organic farm?

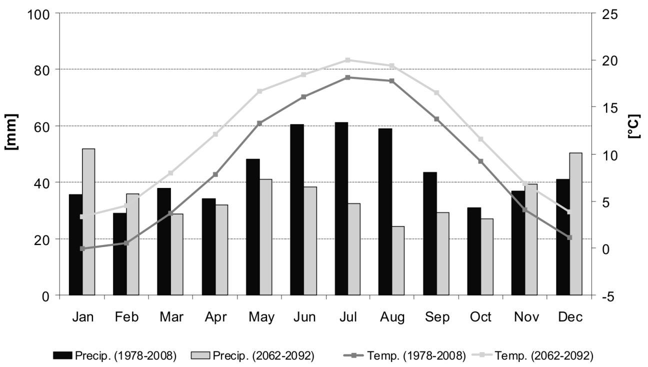


**Figure 1.** Monthly temperatures and precipitation observed from 1978 to 2008 and projected for 2062–2092 by the Angermünde Climate Station; Climate data modeled on the regional statistics model STARS [11].

### *1.2. The Central Issue*

The extent of climate risks can be offset by increasing diversification within an agricultural ecosystem. This means not only introducing a greater diversity in crops and varieties, but also more flexibility in cultivation and tillage methods [12,13]. Such alternative tilling and/or seeding methods help farmers more effectively adapt to changing weather conditions, extending the number of available fieldwork days.

To date, the Wilmersdorf organic farm has used only one method for producing winter wheat.

This work is therefore dedicated to the following questions: *In addition to the standard practice, which winter wheat cultivation methods are most effective in offsetting climate change influences? Which methods contribute most to diversification on a specific farm?*

### 1.3. Alternative Test Methods for Winter Wheat Cultivation

In collaboration, the Wilmersdorf farm manager and the INKA BB field trial project a) developed new cultivation techniques and, b) tested the viability of these methods as alternatives to standard procedures. When evaluating various courses of action, i.e. cultivation methods, for their adaptability to uncertain climate change conditions, *robustness* is an important criterion [14]. Robustness is a system's immunity to a wide range of influences [15]. In this case, the robustness of a new cultivation method is measured by its yield stability over a three-year period under varying field conditions. Hallmarks of these new cultivation methods are reduced tillage and alternative crop rotation. They should be able to improve the N and water supply to winter wheat. These alternative cultivation methods, (Figure 2), and the reduced tillage agricultural tool, the *ring-cutter*, will be described in detail.

A new agricultural tool, the ring-cutter, was used for the first time during the field tests in Brandenburg. This agricultural instrument has cutting rings running diagonally to the driving direction, allowing for an overall, non-turning, shallow tillage (see: http://www.heko-landmaschinen.de). The special ring-cutter construction is intended for soil processing when dryness or sogginess renders ploughing unsuitable. As opposed to the plough, the ring-cutter could be applied to both the dry hilltops and damp hollows on Wilmersdorf farm. The tool should also enable unploughed LGS processing, so that grain mulch seeding (*early sowing* and *oat/ring-cutter* test methods) or *catch crops* can be seeded directly following ring-cutter processing. If ring-cutter processing proves successful, summer crops and early sowing can stay on schedule, despite wet or dry soil. At the same time, shallow processing can reduce the water loss caused by evaporation in ploughed soil. Reduced tillage with the ring-cutter should also retard N-mineralisation, reducing the risk of N-leaching in winter (see test method *oat/ring-cutter*) [16].

#### 1.3.1. Early Sowing of Winter Wheat and a Summer Catch Crop

In the cultivation methods *early sowing* and *catch crop*, the LGS processing date is moved forward to mid-July (summer processing). This early treatment of LGS can either move winter wheat seeding forward or prepare a better seedbed than virgin tillage and an autumn furrow do. Instead of the plough, the ring-cutter is used for early, mechanical LGS killing. The *early sowing* test method repeats ring-cutter processing two or three times between mid-July and mid-August, creating a mulched summer fallow. This fallow protects the soil from water loss that would otherwise occur in living LGS crop transpiration [9]. The mulch also protects from evaporation, reducing water loss from the soil surface (evaporation fallow) [17], while seasonal heavy rains are buffered by the mulch (erosion protection) [18]. At the end of August, the catch crop mixture (50% summer vetch, *Vicia sativa*; 28% buckwheat, *Fagopyrum esculentum*; 16% flax, *Linum usitatissimum*; and 5% *Phacelia*) is sown directly into the summer fallow (mulch seeding). Not turning the earth protects soil life, keeping vertical earthworm channels (macropores) intact and improving infiltration [19–21]. Since it has a longer and stronger plant growth until its dormant season, early sown winter wheat should better absorb the nitrogen mineralised from late summer to early autumn [22,23]. The catch crop mixture should suppress weed growth and prevent an overly lush development of the early sown winter wheat [24]. Furthermore, in autumn the catch crop absorbs any potential nitrogen surplus, conserving it in its biomass throughout the winter. In spring, the frozen catch crop vegetal material mineralizes the soil, supplying the winter wheat with the required nitrogen. Early sown winter wheat develops more profusely in spring, creating better rooting in the subsoil. This is conducive to the nitrogen and water supply in the event of a spring drought. Also, *early sowing* pre-dates winter wheat primary water needs (stem elongation) to a time when the soil should still have enough winter moisture. Furthermore, the early seeding head-start in growth should assure the plants are no longer subjected to drought stress during the grain filling phase [25,26]. The unploughed *early sowing* test method should primarily improve crop establishment and the subsequent grain yield on dry hilltops.

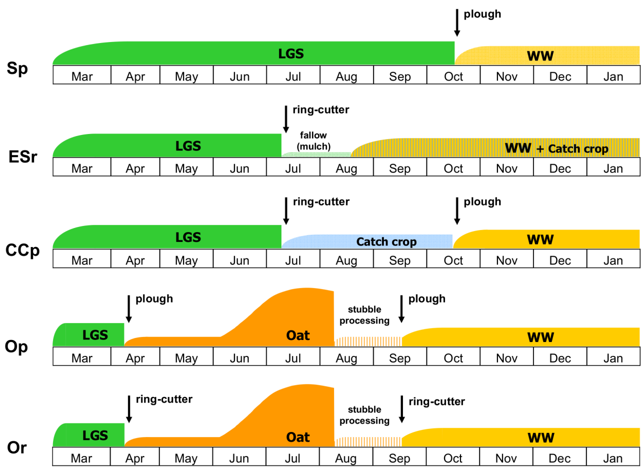


**Figure 2.** Winter wheat (WW) test methods with plough and ring-cutter in the cultivation field tests on the farm Wilmersdorf (2010–2013). Sp: standard practice (plough); ESr: WW early sowing (ring-cutter); CCp: winter wheat following catch crop (plough); Op: winter wheat following oat (plough) and Or: winter wheat following oat (ring-cutter); LGS: Legume-grass swards; personal compilation.

In contrast to *early sowing*, the *catch crop* test method does not have summer fallow. Instead, after repeated processing with the ring-cutter, the same *catch crop* mixture as in *early sowing* is sown at the end of July. The aim of the *catch crop* is to bind nitrogen mobilised by the early LGS tilling in summer, and to convert it into organic material which will have a narrow C/N ratio the following spring [27]. This material activates soil life, improving N resources for winter wheat. Coinciding with the standard autumn furrow, the *catch crop* is ploughed immediately before winter wheat late seeding (mid-October).

#### 1.3.2. Winter Wheat Following an Oat Crop

In the *oat/plough* and *oat/ring-cutter* test methods, LGS tillage takes place in late March. The advantage of springtime tillage over autumn tillage is that the pre-winter mineralisation from LGS residuals, and so nitrate leaching, is nearly non-existent [6]. Compared to autumn tillage, spring tillage usually allows for a better balance between the N release from LGS residuals and N crop up-take [27]. Due to the generally cooler temperatures and a high C/N LGS residual ratio, tillage in spring can also go hand in hand with delayed N mineralisation [6,27]. Since the mineralisation process following spring tillage begins later and lasts longer, often only the second subsequent crop profits from the N provided by multi-annual LGS [6]. For this reason, the *oat/plough* and *oat/ring-cutter* test methods switch crop rotation, growing oats prior to winter wheat. By inserting oats, the N-deployment from organic plant matter (decomposed LGS residuals, straw and oat root residues) is more in sync with winter wheat N up-take the following spring. The advantages of oat as an LGS subsequent crop are its extensive root system and high nutrient up-take [28], while as a winter wheat preceding crop, oat's vegetative growth suppresses weeds. As a recovery crop, oat prevents the spreading of fungal pathogens, such as black root rot (*Gaeumannomyces graminis*) [29,30]. At the same time, the increased winter moisture resulting from climate change should be used productively for early oat cultivation, extending the cultivation period in the future. An earlier vegetation period grants a surplus of available fieldwork days for seeding spring grains [10,31].

To keep future seeding on schedule despite higher winter precipitation (see Figure 1) saturating the soil, the *oat/ring-cutter* test method foregoes ploughing, working the oats with the ring-cutter to establish mulch-till. After harvesting the oats, the stubble is worked with the ring-cutter. The oat straw remains on the field, as its broad C/N ratio helps prevent excessive LGS-residue N release in autumn and subsequent nitrate leaching in winter. In contrast to *standard procedure* virgin tillage, prior oat cultivation improves the winter wheat seedbed preparation and allows for a more flexible seeding schedule. In both oat test methods, winter wheat is sown at the end of September. In test method *oat/ring-cutter*, seeding follows reworking the soil with the ring-cutter—unploughed mulch-till—while test method *oat/plough* entails renewed ploughing. All unploughed test methods are designed to improve dry hilltop yields.

#### 1.3.3. Hypotheses

The robustness of each cultivation method is tested based on the following hypotheses:

(1) The ring-cutter effectively cuts and regulates LGS in both damp and dry soil conditions, where ploughing is restricted.
(2) Compared to the standard practice, winter wheat test methods ploughed in autumn, *catch crop* and *oat/plough*, produce equivalent annual grain yields, on hilltops as well as in hollows.
(3) The unploughed winter wheat test methods *early sowing* and *oat/ring-cutter* are particularly suitable for dry hilltop sites, where, when compared to hollows, the annual grain yields of these test methods come closer to those of standard practices.

## 2. Materials and Methods

### 2.1. Farm Location and Characteristics

The stockless organic farm Wilmersdorf (Bioland growers' association member) is located in the north German lowlands in the northeast of Brandenburg (Uckermark; community Angermünde, district of Wilmersdorf: 53.11431° N; 13.90660° E). The farm has over 1,108 hectares of arable land and 5 hectares of grassland. Almost half of the arable land is used to grow legumes. Forage legume cultivation accounts for the main area (surface area 29%), followed by grain legume cultivation (19%). The remaining half of the arable land is reserved for growing grains, winter rye (28%) and winter wheat (20%), spelt (16%) and spring wheat (15%), as well as winter and spring barley (12% and 9%, respectively). Wilmersdorf has predominately sandy loamy soil and implements the following crop rotation: Alfalfa clover-grass / winter wheat / winter rye / field peas / spelt under sown with alfalfa clover-grass.

### 2.2. Soil Characteristics

Wilmersdorf, located in the upper moraine region, is dominated by a hilly to undulating landscape of hills and hollows (40 to 75 meters above sea level) [32]. Sub-glacial till, lime-free loam or loamy sand prevail [32]. The topsoil is characterised by soil erosion and a low decalcification depth. Predominant is calcite luvisol/gley luvisol (brown soil family), known for both its fertility and its tendency to compress the topsoil foundation [32]. Typical, indigenous catena sequences are, from the hilltop to hollow, calcarite regosol > eroded calcite luvisol > gley luvisol > eutric gley [33]. In dry years, exposed hilltops are prone to yield reductions, while in wet years the loss occurs on the lower slopes and in the hollows [32]. At the same time, the eroded peaks exhibit higher pH values than the hollow depressions (Table 1).

Sandy loam was the predominant soil type in all sub-plots of the pilot facility. Considering a main root zone of 100 mm, sandy loam has a field capacity of 110 mm. In contrast to the hollows, the hilltops are carbonaceous, and average a higher proportion of clay and higher pH values (Table 1). The carbonate level indicates the initial till substrate which topsoil erosion has brought close to the surface. Soil samples found compressed topsoil foundation (soil depth 20–25 cm) on the shallow calcarite regosol hilltops (Ah/C soil). In the samples taken in 2011, the above-mentioned soil conditions were particularly pronounced. Ploughing was limited on the hilltops due to the shallow topsoil and the initial substrate's proximity to the surface.

### *2.3. Climatic Conditions*

The Wilmersdorf climate is characterised by low annual rainfall and frequent dry periods in early summer and autumn. With 517 mm annual rainfall and an average annual temperature of 8.8° C, it is one of the driest regions in Germany [32]. The three experiment years (2010–2013) were partially influenced by extreme weather patterns and high annual precipitation that exceeded the long-term average in all three years (Figure 3).

In 2010, high precipitation in summer (August: 117 mm; annual rainfall: 640 mm), made most fields impassable during both harvest and autumn sowing. 2011 was marked by a very warm and dry April and heavy rains in July (203 mm). Annual rainfall was 693 mm. Winter 2012 brought black frost and a succession of frost/thaw cycles, leading to considerable winterkill. The *early sowing* test method plots were so badly damaged by winterkill that they had to be re-established with spring wheat. After a warm and a partially dry spring, above average precipitation fell in July (annual rainfall 626 mm). A prolonged and snowy 2012/2013 winter was followed by a pre-summer drought in April, then a dry and warm July and August. With an annual rainfall of 583 mm, 2013 was the driest project year.

### *2.4. Test Plots and Implementation*

The field trial was designed as a three-year serial experiment. Complying with crop rotation, the experiments were carried out on a different field each year. Two homogeneous fields (one hilltop, one hollow) were selected on each of these fields by interfacing digital plot, soil and yield maps. The trial cultivation systems were set upon the two sites in fully randomised blocks. Each block contained four plots divided into five sub-plots (20 sub-plots per site/40 sub-plots total). Except for reaping, the 15 m long by 5 m wide plots were worked with the customary combine harvester. The individual steps, deadlines and applied techniques are listed in Table 2. The selected ring-cutter tool had a three-meter working width, six cutting rings and a leaf spring roller for reconsolidating the soil. After the winter wheat harvest, the trial plots were completely ploughed and winter rye was cultivated.

**Table 1.** Soil attributes of the experiment plots.

| Trial No. | Plot No. | $pH_{KCL}$ | $C_{org}$% | $CaCO_3$% | Gravel % | Sand % | Silt % | Clay% | Field Cap.% Vol.$^+$ | Texture class* |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 401-405 | 7.07 | 2.27 | | 4.2 | 60.2 | 29.6 | 10.2 | 18.8 | SaL |
| | 406-410 | 6.91 | 2.54 | | 2.3 | 60.3 | 28.3 | 11.4 | 19.6 | |
| | 411-415 | 6.95 | 2.5 | | 5.7 | 60.7 | 27.9 | 11.4 | 19.6 | |
| | 416-420 | 6.99 | 2.89 | | 4 | 56.9 | 29.7 | 13.4 | 21.7 | |
| 6 | 421-425 | 7.43 | 3 | | 3.9 | 52.1 | 28.2 | 19.7 | 26.2 | SaL |
| | 426-430 | 7.4 | 2.82 | 3.51 | 4 | 57.6 | 28 | 14.4 | 22.4 | |
| | 431-435 | 7.13 | 2.71 | | 1.3 | 59.9 | 28 | 12.1 | 20.3 | |
| | 436-440 | 7.5 | 3.51 | 2.16 | 1.4 | 52.8 | 26.9 | 20.3 | 26.6 | |
| 245 | 481-485 | 6.72 | 2.64 | | 3.3 | 55.9 | 33.8 | 10.3 | 20.9 | SaL |
| | 486-490 | 7.03 | 2.97 | | 1.6 | 54.3 | 33.8 | 11.9 | 22.1 | |
| | 491-495 | 6.01 | 2.39 | | 1.6 | 58.7 | 27.5 | 13.8 | 21.2 | |
| | 496-500 | 6.69 | 2.84 | | 1.5 | 57 | 31.6 | 11.4 | 20.7 | |
| 246 | 501-505 | 7.49 | 2.89 | 7.41 | 1.9 | 53.6 | 31.8 | 14.6 | 23.6 | SaL |
| | 506-510 | 7.56 | 3.14 | 4.86 | 2.7 | 51.8 | 30.8 | 17.4 | 24.6 | |
| | 511-515 | 7.73 | 2.65 | 6.97 | 3.1 | 55.2 | 31.6 | 13.2 | 21.8 | |
| | 516-520 | 7.59 | 2.69 | 7.92 | 4.3 | 54.6 | 29.9 | 15.5 | 22.9 | |
| 253 | 5101-5105 | 7.32 | 2.39 | | 2.5 | 64.9 | 23.9 | 11.2 | 18.7 | SaL |
| | 5106-5110 | 7.44 | 2.83 | | 2.7 | 56.8 | 30.5 | 12.7 | 21.5 | |
| | 5111-5115 | 7 | 3.07 | | 1.7 | 58 | 29.9 | 12.1 | 21.7 | |
| | 5116-5120 | 7.38 | 3.23 | | 1.7 | 55 | 29.1 | 15.9 | 22.1 | |
| 254 | 5121-5125 | 7.5 | 3.24 | 4.11 | 2.7 | 56.8 | 29.2 | 14 | 22.4 | SaL |
| | 5126-5130 | 7.64 | 2.86 | 7.35 | 2.5 | 52.5 | 33.4 | 14.1 | 23.2 | |
| | 5131-5135 | 7.62 | 2.27 | 9.19 | 3.7 | 56.1 | 29.5 | 14.4 | 21.6 | |
| | 5136-5140 | 7.57 | 2.8 | 4.73 | 2.2 | 60.2 | 26.6 | 13.2 | 21 | |

* estimated with the soli texture triangel USDA; $^+$ estimated with the soil water characteristics programm USDA.

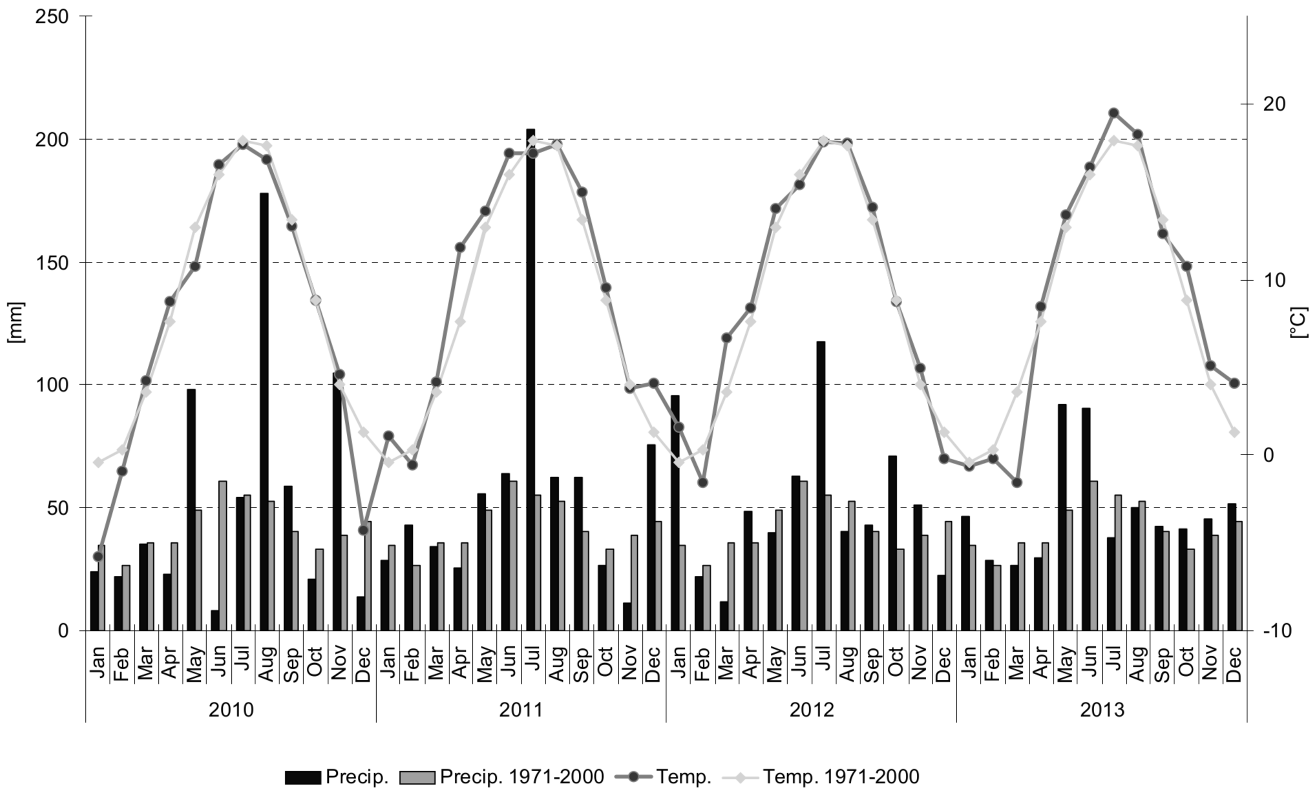


**Figure 3.** Temperature and precipitation regime at Wilmersdorf project location from 2010 to 2013 (project term) and 1971–2000 (long-term average).

**Table 2.** Steps and schedule for the Sp (standard practice; plough), ESr (winter wheat early sowing; ring-cutter), CCp (winter wheat following catch crop; plough), Op (winter wheat following oat; plough) and Or (winter wheat following oat; ring-cutter) test methods of winter wheat cultivation following LGS.

| Year | | | 2010 | | | | | 2011 | | | | | 2012 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variant | Sp | ESr | CCp | Op | Or | Sp | ESr | CCp | Op | Or | Sp | ESr | CCp | Op | Or |
| Ploughing* | | | | 04-04 | | | | | 28-03 | | | | | 26-03 | |
| Ring-cutter+ | | | | | 30-03 | | | | | 24-03 | | | | | 23-03 |
| | | | | | 04-04 | | | | | 28-03 | | | | | 26-03 |
| Oat sowing+ | | | | 05-04 | | | | | 29-03 | | | | | 05-04 | |
| Oat harvest° | | | | 06-08 | | | | | 04-08 | | | | | 20-08 | |
| Mulching LGS-Mixture°° | 31-05 | 31-05 | 31-05 | | | 15-06 | 15-06 | 15-06 | | | 24-05 | 24-05 | 24-05 | | |
| | 09-07 | 09-07 | 09-07 | | | 22-07 | 22-07 | 22-07 | | | 06-07 | 06-07 | 06-07 | | |
| | 09-08 | | | | | | | | | | 23-08 | | | | |
| | 14-10 | | | | | | | | | | | | | | |
| Ring-cutter+ | | 13-07 | 13-07 | 12-08 | 30-03 | | 26-07 | 26-07 | 17-08 | 17-08 | | 09-07 | 09-07 | 23-08 | 23-03 |
| | | 16-07 | 16-07 | 17-09 | 04-04 | | 28-07 | 28-07 | 29-08 | 29-08 | | 12-07 | 12-07 | 17-09 | 26-03 |
| | | 19-07 | 19-07 | | 12-08 | | 17-08 | | | 24-09 | | 03-08 | | | 23-08 |
| | | 12-08 | | | 17-09 | | 29-08 | | | | | 23-08 | | | 17-09 |
| | | | | | | | | | | | | | | | 02-10 |
| Catch crop sowing° | | | 22-07 | | | | | 02-08 | | | | | 16-07 | | |
| Ploughing* | 19-10 | | 19-10 | 20-09 | | 24-10 | | 24-10 | 24-09 | | 16-10 | | 16-10 | 02-10 | |
| Winter wheat sowing° | 19-10 | 26-08 | 19-10 | 22-09 | 22-09 | 25-10 | 31-08 | 25-10 | 27-09 | 27-09 | 18-10 | 23-08 | 18-10 | 18-10 | 18-10 |
| Intercrop sowing° | | 26-08 | | | | | 31-08 | | | | | 23-08 | | | |
| Year | | | 2011 | | | | | 2012 | | | | | 2013 | | |
| Winter wheat harvest | | | 04-08 | | | | | 20-08 | | | | | 01-08 | | |
| Winter rye sowing° | | | 05-10 | | | | | 05-09 | | | | | 20-09 | | |
| Winter rye harvest | | | - | | | | | 01-08 | | | | | 24-07 | | |

* Lemken Opal 90: Mounted reversible plough with four bodies (working depth 25 cm);
+ Ring-cutter (working width 3 m; working depth 6-8 cm);
° Väderstad Drill Rapid 300 C (working width 3 m);
°° Mulching dates depending on the crop height.

### *2.5. Data Compilation and Analysis*

The yields of oat, winter wheat, and subsequent winter rye (2012 and 2013) were assessed by documenting the number of ears per square meter, the thousand kernel weight and the grain yield. The crude protein content in winter wheat, an indication of grain quality, was measured as well as the oat hectolitre weight. The development and structure of crops were determined by visually appraising cultivated plants, weeds and catch crop mixture coverage [34]. Weed appraisal focused on pre-eminent weeds displaying a high degree of both consistency and coverage.

Biomass growth was compiled by taking manual cuts (0.5 $m^2$) from LGS, the oat crop and the summer catch crop. Depending on the test method (Figure 2), two manual LGS cuts were taken from plots of the *early sowing* and the *catch crop* method, and three cuts were taken from standard practice plots. All LGS cuts were taken independently, either before the usual mulching dates or prior to using the ring-cutter for the first time, respectively (Table 2). The LGS cuts from oat fields (Zadok scale 69) and from the summer *catch crop* were taken after buckwheat bloom [8]. To determine the respective yield share, the LGS and oats samples were sorted by hand. The N-input of the second harvest year was determined by calculating LGS biomass yield, leguminosae and N-content. With the N-balance calculator the N-input count was taken from $N_2$-fusion minus gaseous N-losses that arise from mulching [35]. Soil samples to determine Nmin- content were extracted as weather conditions allowed (Pürkhauer drills, soil layer 0–60 cm), i.e. in autumn after winter wheat seeding, at the beginning of vegetation in spring and after the winter wheat harvest. For the extraction of the soil mineral nitrogen, $NH_4$-N and $NO_3$-N 2M KCl solution was used. In 2010, due to drought, one shallower sample (0–30 cm soil layer) was taken after the oat harvest in late summer. The statistical variance analysis was carried out with MIXED procedure (SAS 9.1 statistical software) and subsequently compared to the mean values (Tukey HSD test).

## 3. Results

### *3.1. Preceding Crops—Alfalfa-Clover-Grass and Summer Catch Crops*

In accordance with test method design, the same LGS seed mix was sown on all plots over all three years. Over all three years, no substantial differences in the quantity of biomass growth on hilltops and hollows could be discovered (Table 3). However, there was a great difference in growth quality regarding which species grew on which site. On the hilltops, LGS growth regularly exhibited a higher percentage of alfalfa; in the hollows, more grasses, herbs, white clover and weeds (Table 4).

In 2010 and 2011 until mid-October, catch crop test plots achieved growth between 2.5 and 3.9 t DM $ha^{-1}$, (N up-take from 72 to 100 kg N $ha^{-1}$). In contrast, in 2012, low rainfall in August and unevenly distributed precipitation in September, caused summer catch crop plots to fail (Table 3).

**Table 3.** LGS dry mass yields as well as CCp method catch crop dry mass yields (t DM $ha^{-1}$). Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough); CC: Catch crop.

| Site | Year | Test method | Cut 1 | Cut 2 | Cut 3 | CC |
|---|---|---|---|---|---|---|
| Hollow | 2010 | SP | 4.1 | 3.3 | 2.2 | |
| | | ESr | 4.7 | 4 | | |
| | | CCp | 4.5 | 3.3 | | 3.7 |
| | | HSD | 2.2 | 0.9 | | |
| | | p-value | 0.7179 | 0.0947 | | |
| | 2011 | SP | 5.7 | 5.3 | 4.1 | |
| | | ESr | 5.4 | 5.9 | | |
| | | CCp | 5.7 | 5.9 | | 2.8 |
| | | HSD | 1.3 | 1.4 | | |
| | | p-value | 0.7125 | 0.3542 | | |
| | 2012 | SP | 5 | 2.4 | 4.4 | |
| | | ESr | 4.8 | 2.5 | | |
| | | CCp | 5.1 | 2.7 | | |
| | | HSD | 1.4 | 1.1 | | |
| | | p-value | 0.8631 | 0.7744 | | |
| Hill | 2010 | SP | $4.7^a$ | 4.3 | 2.5 | |
| | | ESr | $4.7^a$ | 3.5 | | |
| | | CCp | $5.8^b$ | 4.6 | | 3.9 |
| | | HSD | 1 | 2.3 | | |
| | | p-value | 0.0318 | 0.3774 | | |
| | 2011 | SP | 4.9 | 4 | 3 | |
| | | ESr | 5.2 | 3.6 | | |
| | | CCp | 5.7 | 4.5 | | 2.5 |
| | | HSD | 2.1 | 3.3 | | |
| | | p-value | 0.571 | 0.6816 | | |
| | 2012 | SP | 4 | $1.7^a$ | 2 | |
| | | ESr | 4 | $2.3^a$ | | |
| | | CCp | 4.7 | $2.4^b$ | | |
| | | HSD | 1.5 | 0.5 | | |
| | | p-value | 0.3866 | 0.0067 | | |

HSD (honestly significant difference);
Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 4.** Yield shares in % of alfalfa, white clover, red clover, grass and herbs in the LGS mixture. Alfal: alfalfa; WC: white clover; RC: red clover; herb.: herbs.

| Site | Year | Alfal. | WC | RC | Grass/herb. |
|---|---|---|---|---|---|
| Hollow | 2010 | 9 | 66 | | 25 |
| | 2011 | 49 | 4 | | 47 |
| | 2012 | 38 | 15 | | 47 |
| Hill | 2010 | 62 | 23 | | 14 |
| | 2011 | 76 | 1 | | 23 |
| | 2012 | 63 | 5 | 1 | 32 |

### *3.2. Preceding Crop Oats*

In 2010 and 2012, oat yields were 21% and 54% higher in the *oat/plough* test method than in the *oat/ring-cutter* test method, respectively (Table 5). In each trial year, the yield difference between the two test methods was more pronounced in the hollows than on the peaks. Only on the hilltops in 2011, where ploughing was limited, (see Section 2.2), did the unploughed *oat ring-cutter* method achieve a 17% higher oat grain yield.

**Table 5.** Oat yield structure—Op and Or methods. Op: Oat variant with plough; Or: Oat variant with ring-cutter; tkw: thousand kernel weight.

| Site | Year | Test method | Ears ($m^2$) | tkw (g) | Grain yield ($t\ ha^{-1}$) | Hectolitre weight (kg) |
|---|---|---|---|---|---|---|
| Hollow | 2010 | Op | 270 | 36.2 | $5.1^a$ | 45.8 |
| | | Or | 211 | 35.8 | $2.9^b$ | 45.9 |
| | | HSD | 76 | 12 | 1.5 | 0.7 |
| | | p-value | 0.0829 | 0.5128 | 0.0214 | 0.1001 |
| | 2011 | Op | 307 | 47.3 | 5.3 | 51.5 |
| | | Or | 280 | 49.1 | 4.6 | 51.4 |
| | | HSD | 41.7 | 4.2 | 2.4 | 2.1 |
| | | p-value | 0.1266 | 0.2744 | 0.4132 | 0.8299 |
| | 2012 | Op | 145 | 41.4 | $3.9^a$ | 48.2 |
| | | Or | 178 | 39.9 | $1.8^b$ | 48.1 |
| | | HSD | 76 | 2.9 | 0.2 | 3.5 |
| | | p-value | 0.2612 | 0.2177 | <.0001 | 0.9349 |
| Hill | 2010 | Op | $243^a$ | 36.2 | $4.2^a$ | 43.9 |
| | | Or | $181^b$ | 36.1 | $3.3^b$ | 45.2 |
| | | HSD | 21.4 | 3.2 | 0.4 | 3.8 |
| | | p-value | 0.0027 | 0.9624 | 0.0076 | 0.3451 |
| | 2011 | Op | 285 | 46.1 | 3.6 | 49.5 |
| | | Or | 274 | 48 | 4.1 | 50.3 |
| | | HSD | 73.8 | 6.2 | 1.6 | 0.9 |
| | | p-value | 0.668 | 0.3883 | 0.3302 | 0.0657 |
| | 2012 | Op | 209 | 41.2 | 4.2 | 47.8 |
| | | Or | 165 | 41.6 | 2.3 | 48.2 |
| | | HSD | 61.8 | 2.3 | 2.3 | 1.6 |
| | | p-value | 0.1082 | 0.6804 | 0.0882 | 0.4824 |

HSD (honestly significant difference);
Different letters indicate significant differences ($\alpha \leq 0.05$).

### *3.3. Winter Wheat*

Among test methods, the winter wheat grain harvest varied considerably. This variance was most pronounced in the years with extreme weather conditions (2011 and 2012; see Section 2.3.).

In 2011 and 2012, winter wheat on the *oat/plough* and *oat-ring-cutter* test plots could not be harvested due to frequent heavy precipitation and a rampant weed infestation (*Tripleurospermum perforatum*). In all years and on all test plots, when harvesting was possible, winter wheat grown with the *oat/ring-cutter* test method produced the lowest grain yield of all test methods—significantly lower on hilltops in 2012 and 2013; and in hollows in 2013 (Table 6). In addition, the hilltop winter wheat in *oat/ring-cutter* test methods exhibited decidedly lower crude protein in 2011 and 2012. There was no great difference in grain yields between the standard procedure and *early sowing* and *catch crop* test methods. Compared to standard practices, however, the *early sowing* method had consistently lower grain yields. In 2011, the crude protein content in *early sowing* was markedly lower than in *standard* and *catch crop* methods. In contrast, in the dry year, 2013, *early sowing* exhibited a much higher thousand kernel weight than *standard* and *catch crop* methods. The *catch crop* method came closest to matching the standard practice in yield and quality. With the exception of *catch crop* in 2013, none of the alternative test methods were able to achieve a higher yield than the standard practice.

### *3.4. Subsequent Crop Winter Rye*

In 2012 and 2013, winter rye was a subsequent crop to winter wheat, bringing in high grain yields, especially in the hollows. With the exception of the thousand kernel weight in the hollows in 2013 there was no discernible difference between the test methods (Table 7).

**Table 6.** Winter wheat yield and quality. Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring-cutter); tkw: thousand kernel weight.

| Site | Year | Test method | Ears (m2) | tkw (g) | Grain yield (t ha-1) | Crude protein (%) |
|---|---|---|---|---|---|---|
| Hollow | 2011 | SP | 256 | 41.9 | 4 | $13.6^a$ |
| | | ESr | 262 | 41.3 | 3.6 | $11.0^b$ |
| | | CCp | 243 | 43.7 | 3.8 | $12.4^a$ |
| | | Op | - | - | - | - |
| | | Or | - | - | - | - |
| | | HSD | 84.3 | 3.4 | 2 | 1.3 |
| | | p-value | 0.7886 | 0.1727 | 0.807 | 0.0025 |
| | 2012 | SP | 197 | 46.6 | 3.1 | 13.9 |
| | | ESr | * | * | * | * |
| | | CCp | 189 | 47 | 2.9 | 13.9 |
| | | Op | - | - | - | - |
| | | Or | - | - | - | - |
| | | HSD | 127.4 | 5.4 | 2.4 | 1.7 |
| | | p-value | 0.8544 | 0.8314 | 0.7934 | 0.9942 |
| | 2013 | SP | 166 | $43.9^a$ | $2.8^a$ | 13 |
| | | ESr | 185 | $48.2^b$ | $2.8^a$ | 12.6 |
| | | CCp | 191 | $42.9^a$ | $2.8^a$ | 12.7 |
| | | Op | 187 | $42.2^a$ | $2.3^a$ | 12.7 |
| | | Or | 181 | $38.4^c$ | $1.0^b$ | 12.7 |
| | | HSD | 74.1 | 3.3 | 0.8 | 1 |
| | | p-value | 0.851 | <.0001 | <.0001 | 0.7514 |
| Hill | 2011 | SP | 270 | $43.9^{ab}$ | $4.6^a$ | $12.8^a$ |
| | | ESr | 237 | $41.1^a$ | $3.5^{ab}$ | $10.3^b$ |
| | | CCp | 250 | $45.8^b$ | $4.5^a$ | $11.4^a$ |
| | | Op | 176 | $41.8^a$ | $3.6^{ab}$ | $9.9^c$ |
| | | Or | 158 | $42.5^a$ | $1.9^b$ | $9.9^c$ |
| | | HSD | 157.3 | 2.9 | 2 | 1.5 |
| | | p-value | 0.1647 | 0.0018 | 0.0078 | <.0001 |
| | 2012 | SP | $170^a$ | 42 | $2.6^a$ | $13.6^a$ |
| | | ESr | * | * | * | * |
| | | CCp | $153^{ab}$ | 40 | $2.5^{ab}$ | $13.7^a$ |
| | | Op | $93^b$ | 40 | $1.3^{ab}$ | $12.6^{ab}$ |
| | | Or | $85^b$ | 44.7 | $1.2^b$ | $11.6^b$ |
| | | HSD | 68.6 | 7.5 | 1.3 | 1.1 |
| | | p-value | 0.0082 | 0.359 | 0.0172 | 0.0009 |
| | 2013 | SP | 218 | $41.7^a$ | $2.6^{ab}$ | 11.5 |
| | | ESr | 177 | $47.1^c$ | $2.6^{ab}$ | 11.9 |
| | | CCp | 188 | $42.6^a$ | $2.9^a$ | 11.7 |
| | | Op | 234 | $40.5^{ab}$ | $2.2^b$ | 11.6 |
| | | Or | 171 | $37.5^b$ | $1.2^c$ | 11.4 |
| | | HSD | 87 | 3.1 | 0.4 | 0.8 |
| | | p-value | 0.1562 | <.0001 | <.0001 | 0.3644 |

*Winterkill damage; HSD (honestly significant difference);
Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 7.** Yield structure—subsequent winter rye crop. Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough) and Or: Winter wheat following oat (ring cutter); tkw: thousand kernel weight.

| Site | Year | Test method | Ears ($m^2$) | tkw (g) | Grain yield (t $ha^{-1}$) |
|---|---|---|---|---|---|
| Hollow | 2012 | SP | 400 | 34.1 | 6.2 |
| | | ESr | 403 | 33.4 | 6 |
| | | CCp | 351 | 35 | 6.4 |
| | | Op | 370 | 33.9 | 5.9 |
| | | Or | 426 | 35.3 | 6.2 |
| | | HSD | 111.3 | 2.6 | 2.2 |
| | | p-value | 0.2842 | 0.2873 | 0.9548 |
| | 2013 | SP | 438 | $31.9^{a}$ | 4.9 |
| | | ESr | 438* | $34.1^{*ab}$ | 6.0* |
| | | CCp | 485 | $32.2^{a}$ | 5 |
| | | Op | 476 | $32.3^{a}$ | 6.3 |
| | | Or | 430 | $35.4^{b}$ | 5.3 |
| | | HSD | 152.2 | 2.3 | 2.4 |
| | | p-value | 0.6883 | 0.0015 | 0.2964 |
| Hill | 2012 | SP | 294 | 35.4 | 5.2 |
| | | ESr | 357 | 33.4 | 5.1 |
| | | CCp | 306 | 34.7 | 4.8 |
| | | Op | 244 | 34.9 | 4.1 |
| | | Or | 278 | 35.1 | 4.6 |
| | | HSD | 124.9 | 3.2 | 2.2 |
| | | p-value | 0.1238 | 0.3836 | 0.5357 |
| | 2013 | SP | 244 | 35 | 3.7 |
| | | ESr | 223* | 37.3* | 2.9* |
| | | CCp | 269 | 36.8 | 4.2 |
| | | Op | 221 | 36.2 | 2.5 |
| | | Or | 269 | 34.7 | 3.3 |
| | | HSD | 180.37 | 5.3 | 5 |
| | | p-value | 0.8397 | 0.6058 | 0.8433 |

*Preceding crop summer wheat;
HSD (honestly significant difference);
Different letters indicate significant differences ($\alpha \leq 0.05$).

### *3.5. N-dynamic*

The N-dynamic in cultivation methods was estimated based on the LGS N-input, N-up-take in the grains and $N_{min}$-contents in the soil. Interdependent on tilling date, biomass yield and the leguminous crop, the LGS provided an N-input from 145 to 352 kg N $ha^{-1}$ in the second harvest year (Table 8). Oats attained the highest nitrogen up-take after LGS tillage and ploughing, taking up more than 100 kg N $ha^{-1}$ in the hollows in 2010 and 2011.

In late summer 2010 (Table 9), $N_{min}$ sampling from the *early sowing* and *catch crop* test plots at the hollow exhibited significantly higher $N_{min}$ values than the other test methods. Prior to sampling, the LGS plots of both test methods were killed in July via root separation with the ring-cutter (see Table 2).

In the autumn of 2011 and 2012, *oat/plough* and partly *oat/ring-cutter* wheat plots exhibited significantly higher $N_{min}$-values than those of the standard practice (Ø +45 kg N $ha^{-1}$; Table 10). Oat plough had the highest $N_{min}$-values of all test methods. In spring, the highest $N_{min}$-values were always observed on standard practice and *catch crop* wheat plots, which had been ploughed at a later date. Compared to the standard practice, *oat/ring-cutter* and *oat/plough* methods had significantly lower $N_{min}$-values in the spring (Hollow 2011–2013). There were no remarkable differences in $N_{min}$-values in samples taken from beneath the subsequent winter rye crop (08.11.2011, 22.10.2012), or taken immediately after the winter wheat harvest (08.02.2013; Table 11). The five highest $N_{min}$-values of all sampling dates were found in the subsequent winter rye crop (max. value, 148 kg N$ha^{-1}$; *oat/ring-cutter* test method).

**Table 8.** N-input and N-uptake in the crop sequence (N kg $ha^{-1}$). Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring cutter).

| Site | Year | Test method | Input LGS | Uptake Oat | Uptake WW | Uptake WR | Balance |
|---|---|---|---|---|---|---|---|
| Hollow | 2010–2012 | SP | 259 | | 83.8 | 83.7 | 0.32 |
| | | ESr | 191 | | 59.5 | 78.2 | 0.31 |
| | | CCp | 180 | | 71.2 | 80.3 | 0.4 |
| | | Op | | $105.8^{a}$ | | 74.6 | |
| | | Or | | $56.2^{b}$ | | 76.2 | |
| | | HSD | | 43.7 | 43.5 | 26.5 | |
| | | p-value | | 0.0447 | 0.3031 | 0.8273 | |
| | 2011–2013 | SP | 267 | | 65.4 | 52 | 0.24 |
| | | ESr | 184 | | | 66 | |
| | | CCp | 211 | | 60.3 | 54.4 | 0.29 |
| | | Op | | 100.4 | | 66.6 | |
| | | Or | | 83 | | 54.4 | |
| | | HSD | | 40.4 | 47.5 | 25 | |
| | | p-value | | 0.2642 | 0.7571 | 0.2373 | |
| | 2012–2013 | SP | 206 | | $55.4^{a}$ | | 0.27 |
| | | ESr | 145 | | $53.2^{a}$ | | 0.37 |
| | | CCp | 146 | | $54.6^{a}$ | | 0.37 |
| | | Op | | 73.2 a | $43.4^{a}$ | | |
| | | Or | | 31.7 b | $18.8^{b}$ | | |
| | | HSD | | 9.2 | 14.3 | | |
| | | p-value | | 0.0007 | <.0001 | | |
| Hill | 2010–2012 | SP | 352 | | $87.4^{a}$ | 69.2 | 0.25 |
| | | ESr | 265 | | $54.2^{bc}$ | 65 | 0.2 |
| | | CCp | 278 | | $77.8^{ab}$ | 60.2 | 0.28 |
| | | Op | | $79.0^{a}$ | $53.8^{bc}$ | 49.5 | |
| | | Or | | $59.0^{b}$ | $29.1^{c}$ | 57.5 | |
| | | HSD | | 10.53 | 32.3 | 27.4 | |
| | | p-value | | 0.0091 | 0.0008 | 0.255 | |
| | 2011–2013 | SP | 222 | | 52.9 a | 47.9 | 0.24 |
| | | ESr | 228 | | | 37.6 | |
| | | CCp | 226 | | $52.3^{a}$ | 55.5 | 0.23 |
| | | Op | | 66.2 | $24.8^{b}$ | 29.7 | |
| | | Or | | 78 | $20.6^{b}$ | 38.5 | |
| | | HSD | | 32 | 25.7 | 64.2 | |
| | | p-value | | 0.3229 | 0.0047 | 0.7404 | |
| | 2012–2013 | SP | 149 | | $45.1^{ab}$ | | 0.3 |
| | | ESr | 156 | | $46.0^{ab}$ | | 0.29 |
| | | CCp | 145 | | $51.3^{a}$ | | 0.35 |
| | | Op | | 69.8 | $37.6^{b}$ | | |
| | | Or | | 39.1 | $20.6^{c}$ | | |
| | | HSD | | 43.4 | 7.4 | | |
| | | p-value | | 0.1094 | <.0001 | | |

HSD (honestly significant difference);
Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 9.** $N_{min}$-values of mulched LGS (Sp), of LGS after ring-cutter root separation (ESr), of catch crop mixture (CCp) and of oat stubble (Op und Or)—soil layer 0–30 cm. Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough) Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring-cutter); HSD (honestly significant difference).

| | | $N_{min}$ kg ha$^{-1}$ (0–30 cm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date of sampling | Site | Sp | ESr | CCp | Op | Or | $\overline{x}$ | HSD | p-value |
| 11-08-2010 | Hollow (2010) | 35.8$^{b}$ | 109.8$^{a}$ | 96.9$^{a}$ | 42.4$^{b}$ | 22.5$^{b}$ | 61.4 | 28.1 | $<$.0001 |
| | Hill (2010) | 34.6$^{b}$ | 89.5$^{a}$ | 73.5$^{ac}$ | 43.0$^{bc}$ | 20.0$^{b}$ | 52.1 | 32.9 | $<$.0001 |

Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 10.** $N_{min}$-values, (soil layer 0–60 cm) beneath winter wheat after autumn seeding and at the onset of spring vegetation. Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring-cutter).

| | | $N_{min}$ kg ha$^{-1}$ (0–60 cm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date of sampling | Site | Sp | ESr | CCp | Op | Or | $\overline{x}$ | HSD | p-value |
| 05-04-2011 | Hollow (2010) | 79.7$^{a}$ | 36.7$^{bc}$ | 48.6$^{c}$ | 25.0$^{b}$ | 22.2$^{b}$ | 42.4 | 22.4 | $<$.0001 |
| | Hill (2010) | 48.7$^{a}$ | 16.9$^{b}$ | 36.0$^{a}$ | 15.4$^{b}$ | 15.6$^{b}$ | 26.5 | 15.4 | $<$.0001 |
| 01-11-2011 | Hollow (2011) | 66.9$^{a}$ | 73.9$^{a}$ | 77.5$^{a}$ | 115.6$^{b}$ | 90.3$^{a}$ | 84.8 | 39.5 | 0.0153 |
| | Hill (2011) | 49.0$^{a}$ | 79.2$^{ac}$ | 53.0$^{a}$ | 106.6$^{c}$ | 98.7$^{c}$ | 77.3 | 38.5 | 0.0262 |
| 24-04-2012 | Hollow (2011) | 99.5$^{a}$ | * | 114.7$^{a}$ | 42.9$^{b}$ | 42.0$^{b}$ | 74.8 | 51.5 | 0.0003 |
| | Hill (2011) | 101.8$^{ab}$ | * | 119.3$^{ab}$ | 78.3$^{ab}$ | 73.7$^{b}$ | 93.3 | 55 | 0.0258 |
| 22-10-2012 | Hollow (2012) | 46.4$^{a}$ | 61.1$^{ab}$ | 33.7$^{a}$ | 77.4$^{b}$ | 54.1$^{a}$ | 54.5 | 22.8 | 0.0007 |
| | Hill (2012) | 34.0$^{a}$ | 48.1$^{ab}$ | 39.7$^{a}$ | 74.2$^{b}$ | 59.0$^{ab}$ | 51 | 26.4 | 0.0029 |
| 06-03-2013 | Hollow (2012) | 76.1$^{a}$ | 38.8$^{b}$ | 47.3$^{b}$ | 38.6$^{b}$ | 34.0$^{b}$ | 46.9 | 21.7 | 0.0003 |
| | Hill (2012) | 51.6 | 41.5 | 52.6 | 37.3 | 36.2 | 43.8 | 21.8 | 0.0897 |

*Winterkill damage; Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 11.** $N_{min}$-values (soil layer 0–60 cm) under WR subsequent to WW (08.11.2011; 22.10.2012) and shortly after WW harvest (02.08.2013). Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring-cutter); HSD (honestly significant difference).

| | | $N_{min}$ kg ha$^{-1}$ (0–60 cm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date of sampling | Site | Sp | ESr | CCp | Op | Or | $\overline{x}$ | HSD | p-value |
| 08-11-2011 | Hollow (2010) | 120 | 94.5 | 84.0 | 125.7 | 148.5 | 114.5 | 111.5 | 0.4086 |
| | Hill (2010) | 130.4 | 99.7 | 137.3 | 96.3 | 122.5 | 117.2 | 82.9 | 0.4461 |
| 22-10-2012 | Hollow (2011) | 97 | 70.6 | 87.3 | 50.3 | 66.2 | 74.2 | 64.5 | 0.2293 |
| | Hill (2011) | 104.1 | 121.3 | 116.8 | 66.5 | 97.1 | 101.1 | 75.3 | 0.2184 |
| 02-08-2013 | Hollow (2012) | 41.1 | 35.3 | 40.5 | 38 | 33.4 | 37.6 | 12.3 | 0.2672 |
| | Hill (2012) | 28.5 | 29.9 | 30.2 | 31.1 | 24.6 | 28.8 | 9.8 | 0.306 |

### *3.6. Weeds*

Weed distribution varied on the different sites and test method plots. In all experimental years, the weed population in oats and winter wheat was more pronounced in the hollows than on the hilltops.

On average, the standard practice and *catch crop* test method (autumn ploughing and late seeding) had the lowest weed dockage, the weed coverage ratio (WCR) in both methods being nearly identical. In comparison, the *early sowing* WCR was from distinctly to significantly higher in each year. On the *oat/ring-cutter* plots there was usually a higher WCR (Table 12) and/or a higher weed biomass (Table 13) in established oat and winter wheat cultures than on the *oat/plough* (Op) test plots. In addition to these quantitative differences, specific differences were found in weed group composition on the varying sites and in the varying test methods.

The prior LGS crops generated weed flora—alfalfa (*Medicago sativa L.*), red and white clover (*Trifolium repens L.* and *Trifolium pratense L.*) as well as perennial ryegrass (*Lolium perenne L.*) and couch grass (*Agropyron repens L.*)—on all locations and test methods. Comparing standard practices and ploughed test methods (*catch crop*, *oat/plough*) to the unploughed test methods (*early sowing* and *oat/ring-cutter*) (Table 13), alfalfa did not regrow in ploughed methods, neither in the preceding oat crop nor or in winter wheat. In 2011, however, alfalfa did regrow on standard practices and *catch crop* hilltop plots because the plough could not optimally turn the soil in autumn. Besides alfalfa, the weed population was dominated by, in descending order, creeping thistle (*Cirsium arvense L.*), scentless chamomile (*Tripleurospermum perforatum*), poppy (*Papaver rhoeas L.*), common chickweed (*Stellaria media L.*), larkspur (*Consolida regalis Gray*) and veronica (*Veronica chamaedrys L.*). These species varied within sites and procedures. In the hollows and in the unploughed test methods, creeping thistle was much more dominant (Table 14), particularly in the *oat/ring-cutter* winter wheat. In the hollows and on one hilltop, scentless chamomile dominated, mainly in the early sowing, *oat/ring-cutter* and *oat/plough* winter wheat test methods (cover ratio, 75–90%). In 2011 and 2012, a rampant odourless chamomile infestation caused winter wheat crop failure in *oat/plough* and *oat/ring-cutter* hollows.

## 4. Discussion

The experimental cultivation methods were carried out from 2010 to 2013 and were at times subject to extreme weather conditions. Only 2013 came close to long-term averages and predicted climate changes, such as pre-summer drought (see Figure 3). With this in mind, the following discussion addresses the extent to which the tests provide a practical alternative to standard practices and if they can contribute to diversifying winter wheat cultivation.

### *4.1. Reduced Tillage With the Ring-Cutter*

The hypothesis that the ring-cutter can effectively kill and regulate LGS in both wet (spring) and dry (summer) soils was confirmed—LGS secondary growth coverage on unploughed oat and wheat plots was the same height as on ploughed plots. The tool's cutting technique - a shallow, vertical undercutting of the upper topsoil - separates the alfalfa sprout shaft below the root crowns, effectively impeding regrowth. In contrast to the plough, ring-cutter tractive power requirements are low and operating speed (11 km $h^{-1}$) is remarkably fast. Nonetheless, the tool required two to four working cycles to prepare the plots for mulch seeding after the two-year LGS cultivation. Further drawbacks to the ring-cutter were much lower grain yields in two of the three years on *oat/ring-cutter* and winter wheat plots and less N-availability than *oat/plough* plots. Ring-cutter implementation only reached higher oat yields than *oat/plough* on the shallow hilltop in the 2011 test method. Numerous other studies substantiate that reduced tillage in organic farming results in lower yields and lower N-availability [19,36–39]. Reduced tillage limits N-availability by delaying soil organic matter (SOM) mineralisation, due to minimal aeration [19] and poor soil warming in the spring, particularly when densely mulched [40]. Especially in spring, unprocessed earth is often cooler and soggier than ploughed soil, hindering both germination and the initial growth of summer grains [41]. Reduced soil processing can also lead to increased compression in untreated layers [18,39] and to accumulated SOM in the upper soil layer [42], as confirmed by ring-cutter processing research conducted at the ZALF Müncheberg experimental station where much higher soil compression limited root penetration of winter grains [43]. Limited N, compressed soil and thwarted root growth impede a plant's ability to absorb nutrients, which may have caused the much lower oat and winter wheat harvests [37]. In addition to these factors, the ring-cutter plots displayed dense weed growth (Tables 12 and 13); typical for reduced tillage in organic farming [19,44]. Shallow ring-cutter processing causes weed seeds to remain close to the surface, providing excellent germination conditions. Perennial species such as couch grass and creeping thistle thrive under reduced tillage [45].

Bearing all this in mind, it becomes clear that the results of reduced tillage are highly dependent on the time of ring-cutter processing, on crop rotation selection and on weather conditions, as confirmed by the completely unploughed *oat/ring-cutter* and *early sowing* test methods [18]. While *oat/ring-cutter* did not generate stable oats or winter wheat grain yields, the early sowing wheat yields of two trial years did not deviate greatly from standard procedure yields. Hence, reduced soil processing can be successful when applied to pertinent sites and adapted to the entire cultivation system, i.e. alterations in crop rotation, seeding and the catch crop [19].

**Table 12.** Percentage weed coverage in all winter wheat cultivation methods (Sp, ESr, CCp Op and Or). Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring-cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring-cutter); HSD (honestly significant difference).

| | | | Weed coverage % | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Site | Zadoks scale | Sp | ESr | CCp | Op | Or | $\overline{x}$ | HSD | p-value |
| 27-04-2011 | Hollow (2010) | 30–37 | $11^{a}$ | $71^{b}$ | $16^{a}$ | $71^{b}$ | $94^{b}$ | 53 | 29.7 | <.0001 |
| | Hill (2010) | 32–39 | $19^{a}$ | $64^{b}$ | $19^{a}$ | $26^{a}$ | $75^{b}$ | 41 | 32.8 | 0.0002 |
| 28-06-2011 | Hollow (2010) | 77–83 | $34^{a}$ | $64^{b}$ | $48^{ab}$ | $91^{c}$ | $99^{c}$ | 67 | 25.5 | <.0001 |
| | Hill (2010) | 77–83 | 29 | 50 | 34 | 24 | 50 | 37 | 49.1 | 0.3428 |
| 03-05-2012 | Hollow (2011) | 30–34 | $51^{a}$ | * | $48^{a}$ | $97^{b}$ | $93^{b}$ | 72 | 36.1 | <.0001 |
| | Hill (2011) | 30–34 | $12^{a}$ | * | $11^{a}$ | $8^{a}$ | $54^{b}$ | 21 | 39.4 | 0.0036 |
| 16-07-2012 | Hollow (2011) | 83–87 | $73^{a}$ | * | $71^{a}$ | $95^{b}$ | $90^{ab}$ | 83 | 21.5 | 0.0021 |
| | Hill (2011) | 83–87 | 49 | * | 40 | 45 | 43 | 44 | 42.1 | 0.5208 |
| 23-04-2013 | Hollow (2012) | 29–31 | $12^{a}$ | $73^{b}$ | $6^{a}$ | $8^{a}$ | $34^{c}$ | 26 | 15.9 | <.0001 |
| | Hill (2012) | 29–31 | $9^{ac}$ | $71^{b}$ | $5^{a}$ | $6^{a}$ | $21^{c}$ | 22 | 15.4 | <.0001 |
| 24-05-2013 | Hollow (2012) | 41–49 | $31^{a}$ | $68^{b}$ | $38^{a}$ | $36^{a}$ | $59^{b}$ | 46 | 24.5 | 0.0017 |
| | Hill (2012) | 41–49 | $20^{ac}$ | $66^{b}$ | $17^{ac}$ | $10^{a}$ | $33^{c}$ | 29 | 21.3 | <.0001 |

*Winterkill damage; Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 13.** Weed biomass in oats (at blossoming), Op and Or methods. Op: Oat (plough); Or: Oat (ring-cutter); HSD (honestly significant difference).

| | | | Weed DM t ha$^{-1}$ | | | |
|---|---|---|---|---|---|---|
| Date | Site | Op | Or | | HSD | p-value |
| 30-06-2010 | Hollow (2010) | $1.2^{a}$ | $2.5^{b}$ | 1.8 | 1.2 | 0.0491 |
| | Hill (2010) | 0.7 | 1.6 | 1.2 | 0.7 | 0.1373 |
| 09-06-2011 | Hollow (2011) | 0.9 | 1.3 | 1.1 | 1.4 | 0.4211 |
| | Hill (2011) | 0.7 | 0.3 | 0.5 | 0.7 | 0.216 |
| 12-06-2012 | Hollow (2012) | 1.8 | 2.2 | 2 | 0.7 | 0.2211 |
| | Hill (2012) | 0.8 | 1 | 0.9 | 1.2 | 0.4896 |

Different letters indicate significant differences ($\alpha \leq 0.05$).

**Table 14.** Dominance (dom.; %) and frequency (freq.; %) of *Cirsium avense* (Ca) and *Medicago sativa* (Ms) in oat and winter wheat (SP, ESr, CCp, Op and Or test methods). Sp: Standard practice (plough); ESr: Early sowing of winter wheat (ring cutter); CCp: Winter wheat following catch crop (plough); Op: Winter wheat following oat (plough); Or: Winter wheat following oat (ring cutter).

| | | Sp | | | | ESr | | | | CCp | | | | Op | | | | Or | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ca | | Ms | | Ca | | Ms | | Ca | | Ms | | Ca | | Ms | | Ca | | Ms | |
| Oat | | | | | | | | | | | | | | | | | | | | | |
| n | Site | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. |
| 32 | Hollow (2010) | | | | | | | | | | | | | 12 | 38 | | | 29 | 84 | | |
| 32 | Hill (2010) | | | | | | | | | | | | | | | 16 | 100 | 20 | 34 | 23 | 20 |
| 12 | Hollow (2011) | | | | | | | | | | | | | 5 | 8 | 12 | 100 | 12 | 58 | 8 | 100 |
| 12 | Hill (2011) | | | | | | | | | | | | | | | 19 | 100 | | | 13 | 100 |
| 4 | Hollow (2012) | | | | | | | | | | | | | 8 | 25 | | | 25 | 75 | 4 | 75 |
| 4 | Hill (2012) | | | | | | | | | | | | | | | 2 | 75 | 22 | 50 | 5 | 100 |
| Winter Wheat | | | | | | | | | | | | | | | | | | | | | |
| n | Site | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. | dom. | freq. |
| 20 | Hollow (2010) | 5 | 20 | 5 | 5 | 7 | 45 | 6 | 10 | 14 | 75 | | | 9 | 45 | | | 25 | 85 | | |
| 20 | Hill (2010) | 13 | 20 | 14 | 35 | 22 | 20 | 6 | 20 | 12 | 55 | 8 | 20 | 4 | 15 | 4 | 20 | 10 | 45 | 7 | 20 |
| 8 | Hollow (2011) | 13 | 25 | 15 | 25 | | | * | * | 17 | 88 | 5 | 13 | 6 | 13 | | | 25 | 100 | | |
| 8 | Hill (2011) | | | 20 | 100 | | | * | * | | | 14 | 100 | 3 | 25 | | | 8 | 13 | | |
| 8 | Hollow (2012) | 8 | 13 | 6 | 50 | 15 | 38 | 8 | 25 | 19 | 63 | 9 | 38 | 13 | 25 | | | 33 | 100 | 4 | 13 |
| 8 | Hill (2012) | | | 8 | 75 | 9 | 25 | 6 | 25 | 12 | 13 | 8 | 88 | | | | | 12 | 63 | 8 | 13 |

### 4.2. Winter Wheat Early Sowing and Summer Catch Crop Test Methods

In the test methods *early sowing* and *catch crop*, LGS processing takes place in the summer. The ring-cutter was used to sever LGS roots by shallowly working the topsoil, even in dehydrated soil (i.e. in June 2010). August 2010 $N_{min}$-samples proved that early ring-cutter processing releases significant N-quantities in late summer (up to 109 kg N $ha^{-1}$) for *early sowing* and summer *catch crops* (see Table 9). Heavy rains in August and November 2010 and in July 2011 caused above average precipitation, possibly leading to nitrate leaching and loss in late summer and autumn, especially in 2010, in these two test methods. Further indication of such losses is the significantly lower $N_{min}$-value in early sowing and partly in catch crop in spring 2011, when compared to standard practices.

On the other hand, in 2010 and 2011, *catch crop* plots developed vigorous cover crops that were able to absorb a portion of the mineralised nitrogen by October (up to 86 kg N $ha^{-1}$). Other studies came to similar results with an early catch crop after clover-grass tilling [6]. Compared to standard procedures, the summer catch crop organic material provided a slightly improved N-supply for winter wheat in spring. This is supported by increased $N_{min}$-values on catch crop plots in spring 2012. Despite the possible catch crop nitrate transfers, yields were comparable to standard yields, confirming the hypothesis that the catch crop winter wheat test method ploughed in autumn produces equivalent annual grain yields, on hilltops as well as in hollows, where the other test methods reported yield losses. As to location and weather conditions, the *catch crop* test method proved the hardiest.

Although the *early sowing* test method yields did not differ greatly from standard practices, compared to *catch crop*, *early sowing* yield was characterised by low stability and robustness. In 2012, early sown winter wheat was particularly susceptible to winterkill and in 2011, contained a much lower crude protein. The *early sowing* test method also had a high weed content despite the catch crop mixture, which is typical in *early sown* crops [46]. In 2013, with an early drought in April and dry summer months, early sowing came closest to matching standard practice yields. Possibly the more abundant pre-winter growth, followed by a cold and snowy winter in 2012/2013, allowed early sowing winter wheat to exploit the winter moisture and take up nitrogen early, as confirmed by much higher $N_{min}$-values on early sowing plots the previous autumn and decidedly lower ones in spring 2013. Due to the developmental advantage of *early sowing*, winter wheat was perhaps less affected by water shortages in April (stem elongation) and drought in July during the grain-filling phase [25,26]; an idea supported by the significantly higher thousand kernel weight in this year (Table 6). Overall, the *early sowing* test method shows how heavily grain yields depend on cultivation procedure and weather conditions throughout the year, and that unploughed *early sowing* is not necessarily synonymous with minimal yield. The only *early sowing* location effect was weed pressure. This was less pronounced on hilltops and therefore advocates unploughed processing. Based on the grain yield, the *early sowing* test method is not particularly suitable for dry knoll locations, as was otherwise proposed in hypothesis 3.

### 4.3. Winter Wheat Following Oat

Studies suggesting oat as a good LGS exploiter are confirmed by their results [28]. Especially in the *oat/plough* test method and in the damp hollows, oats were able to take up high levels of mineralised LGS nitrogen in spring (up to 105 kg N $ha^{-1}$). With a high N-supply, *oat/plough* strongly suppressed weed growth [29].

*Oat/plough* and *oat/ring-cutter* test methods showed high $N_{min}$-values (up to 115.6 kg N $ha^{-1}$ on *oat/plough*; 98.7 kg N $ha^{-1}$ on *oat/ring-cutter*) at the beginning of November 2011 and the end of October 2012 despite high N-deprivation and an early winter wheat sowing date in 2011. In contrast to standard practice and *catch crop*, *oat/plough* and *oat/ring-cutter* exhibited lower $N_{min}$-content in the spring than in autumn, which points to nitrate leaching into deeper soil layers after rainy and cold winter months. In both winters, 2011/2012 (205 mm) and 2012/2013 (149 mm), rainfall from November to February was above field capacity (110 mm; see Section 2.2.).

Despite summer crop cultivation after springtime LGS tilling, there may be an increased risk of nitrate leaching the following winter [27]. This risk can be offset by establishing a second subsequent crop in early autumn, ensuring a high and rapid N-up-take. Winter wheat N-uptake (10–30 kg N $ha^{-1}$) in autumn is less pronounced than other grains (for example, winter rye with 30–50 kg N $ha^{-1}$) [47]. Consequently, winter wheat sown on *oat/plough* and *oat/ring-cutter* plots at the end of September (2010 and 2011) and in mid-October 2012 only minimally prevented nitrate leaching.

In the spring, *oat/plough* and *oat/ring-cutter* winter wheat plots were unable to compete against odourless chamomile. This multiyear species has a fibrous and deep-reaching root system, asserting its dominance especially on wet and compacted terrain [48]. Without weed control, odourless chamomile can overrun a winter wheat grain yield by up to 90% [48]. In the wet years 2011 and 2012, this was irrefutably confirmed in the hollows, locations particularly vulnerable to crop failure [32]. In summary, despite spring tillage and an oat insertion, the nitrogen supply for winter wheat was not improved. Also, the *oat/plough* and *oat/ring-cutter* test methods were highly susceptible to weeds. Only on the hilltops and in the dry year 2013 was *oat/plough* winter wheat yield comparable to standard practices, contrary to hypothesis 2. In each trial year and compared to standard practice, the *oat/ring-cutter* winter wheat hilltop harvests produced a smaller deficit margin than harvests in the hollows did. According to hypothesis 3, the oat method is more suitable for hilltops. However, it is not a viable alternative to standard cultivation practices as its yield levels are much lower.

## 5. Conclusion and Outlook

When it comes to adapting cultivation methods to climate changes, greater diversity is an effective risk management strategy for agricultural enterprises [12]. Practically applied, cultivation and soil processing methods must nurture crop robustness. The unpredictable influences of our changing climate demand crops that are insensitive to a broad spectrum of influences [15]. The field test cultivation methods revealed distinctly variable degrees of robustness when it came to growth sites and weather conditions. In every field test year, the standard practice and the *catch crop* test method produced relatively hardy grain and stable crops on all plots. Waiving LGS virgin tilling in autumn as well as improving work-cycle peaks make *catch crop* a viable alternative, contributing to winter wheat diversification. Assuming that future climate changes lead to less winter frosts and therefore less risk of winterkill, the early sowing test method could be an equally feasible option for winter wheat diversification [5]. This is clearly shown in early sowing yield levels which were comparable to standard practice yields during the dry year 2013. The *oat/plough* and *oat/ring-cutter* test methods were far more precarious than standard practices or the *early sowing* and *catch crop* test methods. Both oat test methods are highly site and weather sensitive, which resulted in two years of failed winter wheat crops in the soggy hollows. Assuming that climate change brings an increase in heavy rainfall [5], the weaknesses of *oat/ring-cutter* and *oat/plough* (saturated hollows and rampant weed infestation) make this test method impracticable.

Ring-cutter processing proved to be overall practical, and particularly suited to organic farming needs (multiple-year LGS tillage). However, the denser weed growth, lower N mineralisation and lower grain yields, clearly proves it cannot replace the plough. Nonetheless, as a flexible, manageable tool, the ring-cutter is indeed an alternative on fields where site or weather conditions create severe ploughing risks, such as ploughing depth compaction and hilltop erosion. Climate changes are also changing the customary ploughing and/or soil processing dates [4]. The ring-cutter can help to increase the number of fieldwork days, allowing for LGS processing on both wet and dry soil. The field tests made evident, however, that reduced ploughing must go hand in hand with adjusting cultivation methods and scheduling. The ploughing in spring and autumn resulted in severely reduced oat and winter wheat yields, which was not the case when ploughing in summer. This confirms observations in organic farming that timing is often more decisive than method when it comes to N-supply and weed regulation [49]. If an appropriate moment is not seized, the ensuing consequences cannot be offset by turning to short-term resources, as is the case in conventional farming [9]. This is a distinctive issue and climate change adaptation is a unique and demanding process for organic farmers [2]. There are no universally applicable measures for increasing diversification and robustness on organic farms. A farm's individual site and operating needs must be taken into account to bring robustness to the entire system [50]. In order to identify and develop specific measures for adapting organic farms to climate changes, on-site projects such as this one are indispensable.

## Acknowledgments

This work was funded by the Federal Ministry of Education and Research (BMBF), Germany, by the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), Germany and by the Ministry of Science, Research and Culture (MWFK), Brandenburg. We thank Mr. Stefan Palme, organic farmer, for his expert advice and for allowing the experiments to be conducted on Wilmersdorf.

## References

[1] Milestad R, Dedieu B, Darnhofer I, Bellon S. Farm and farmers facing change: The adaptive approach. In: Darnhofer I, Gibbon D, Dedieu B, editors. Farming Systems Research into the 21st Century: The New Dynamic. Dordrecht: Springer Netherlands; 2012. pp. 365–385.

[2] Bloch R, Knierim A, Häring AM, Bachinger J. Increasing the adaptive capacity of organic farming systems in the face of climate change using action research methods. Organic Agriculture. 2015; Available from: http://dx.doi.org/10.1007/s13165-015-0123-5.

[3] Pang XP, Letey J. Organic Farming Challenge of Timing Nitrogen Availability to Crop Nitrogen Requirements. Soil Science Society of America Journal. 2000;64:247–253.

[4] Reyer C, Bachinger J, Bloch R, Hattermann FF, Ibisch PL, Kreft S, et al. Climate change adaptation and sustainable regional development: a case study for the Federal State of Brandenburg, Germany. Regional Environmental Change. 2012;12(3):523–542.

[5] Gerstengarbe FW, Badeck F, Hattermann F, Krysanova V, Lahmer W, Lasch P, et al.. Gerstengarbe FW, editor. Studie zur klimatischen Entwicklung im Land Brandenburg bis 2055 und deren Auswirkungen auf den Wasserhaushalt, die Forst- und Landwirtschaft sowie die Ableitung erster Perspektiven. Potsdam;.

[6] Heß J. Kleegrasumbruch im Organischen Landbau: Stickstoffdynamik im Fruchtfolgeglied Kleegras - Kleegras - Weizen - Roggen [Dissertation]. Rheinische Friedrich-Wilhelms-Universität Bonn, Department of Agronomy. Bonn, Germany; 1989.

[7] Stanford, G, Epstein E. Nitrogen Mineralization-Water

Relations in Soils. Soil Science Society of America. 1974;38:103–107.

[8] Zadoks JC, Chang TT, Konzak CF. A Decimal Code for the Growth Stages of Cereals. Weed Research. 1974;14:415–421.

[9] Eitzinger J, Kersebaum KC, Formayer H, editors. Landwirtschaft im Klimawandel: Auswirkungen und Anpassungsstrategien für die Land- und Forstwirtschaft in Mitteleuropa. 1st ed. Clenze, Germany: Agrimedia; 2009. Available from: http://www.gbv.de/dms/zbw/600031977.pdf/http://de.agrimedia.com/libeconomy/shop/detail.php?id=268.

[10] Trnka M, Olesen JE, Kersebaum KC, Skjelvåg AO, Eitzinger J, Seguin B, et al. Agroclimatic conditions in Europe under climate change. Global Change Biology. 2011;17(7):2298–2318.

[11] Bloch R, Wechsung F, Heß J, Bachinger J. Climate change impacts of legume-grass swards: implications for organic farming in the Federal State of Brandenburg, Germany. Regional Environmental Change. 2015;15(2):405–414.

[12] Lin BB. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. BioScience. 2011;61(3):183–193.

[13] Smit B, Skinner M. Adaptation Options in Agriculture to Climate Change: a typology. Mitigation and Adaptation Strategies for Global Change. 2002;7:85–114.

[14] Hallegate S. Strategies to adapt to an uncertain climate change. Global Environmental Change. 2009;19:240–247.

[15] Birkmann J, Böhm HR, Buchholz F, Büscher D, Daschkeit A, Ebert S, et al. Glossar Klimawandel und Raumentwicklung: 2. überarbeitete Fassung. E-Paper der ARL. 2013;(10).

[16] Askegaard M, Olesen JE, Rasmussen IA, Kristensen K. Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. Agriculture, Ecosystems and Environment. 2011;142:149–160.

[17] McMillen M. The Effect of Mulch Type and Thickness on the Soil Surface Evaporation Rate. Horticulture and Crop Science. 2013;Available from: http://digitalcommons.calpoly.edu/hcssp/22.

[18] Tebrügge F, Düring RA. Reducing tillage intensity - a review of results from a long-term study in Germany. Soil & Tillage Research. 1999;53:15–28.

[19] Peigné J, Ball BC, Roger-Estrade J, David C. Is conservation tillage suitable for organic farming? A review. Soil Use and Management. 2007;23:129–144.

[20] Kladivko EJ. Tillage systems and soil ecology. Soil & Tillage Research. 2001;61:61–76.

[21] Holland JM. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems & Environment. 2004;103:1–25.

[22] Myrbeck A, Stenberg M, Rydberg T. Establishment of winter wheat—Strategies for reducing the risk of nitrogen leaching in a cool-temperate region. Soil & Tillage Research. 2012;120:25–31.

[23] Thomsen IK, Lægdsmand M, Olesen JE. Crop growth and nitrogen turnover under increased temperatures and low autumn and winter light intensity. Agriculture, Ecosystems and Environment. 2010;139((1-2)):187–194.

[24] Liebman M, Dyck E. Crop Rotation and Intercropping Strategies for Weed Management. Ecological Applications. 1993;3(1):92–122.

[25] Nendel C, Kersebaum KC, Mirschel W, Wenkel KO. Testing farm management options as climate change adaptation strategies usingthe MONICA model. European Journal of Agronomy. 2012;52:47–56.

[26] Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, et al. Impacts and adaptation of European crop production systems to climate change. European Journal of Agronomy. 2011;34:96–112.

[27] Berry PM, Sylvester-Bradley R, Philipps L, Hatch DJ, Cuttle SP, Rayns FW, et al. Is the productivity of organic farms restricted by the supply of available nitrogen? Soil Use Management. 2002;18:248–255.

[28] Watson CA, Baddeley JA, Edwards AC, Rees RM, Walker RL, Topp CFE. Influence of ley duration on the yield and quality of the subsequent cereal crop (spring oats) in an organically managed long-term crop rotation experiment. Organic Agriculture. 2011;1(3):147–159.

[29] Seavers GP, Wright KJ. Crop canopy development and structure influence weed suppression. Weed Research. 1999;39(4):319–328.

[30] Lemanczyk G, Sadowski CK. Fungal communities and health status of roots of winter wheat cultivated after oats and oats mixed with other crops. BioControl. 2002;47(3):349–361.

[31] Kaukoranta T, Hakala K. Impact of spring warming on sowing times of cereal, potato and sugar beet in Finland. Agricultural and Food Science. 2008;17:165–176.

[32] Schmidt R. In: Flade M, editor. Naturräumliche Gliederung von Landschaften. Wiebelsheim, Germany: Quelle & Meyer; 2003. pp. 40–45.

[33] Wirth SJ. Soil Microbial Properties Across an Encatchment in the Moraine, Agricultural Landscape of Northeast Germany. Geomicrobiology Journal. 1999;16(3):207–219.

[34] Wilbois KP, Schwab A, Fischer H, Bachinger J, Palme S, Petersen H, et al. Leitfaden für Praxisversuch: Eine Anleitung zur Planung, Durchführung und Auswertung von Praxisversuchen. Kooperationsgemeinschaft: FiBL Deutschland e.V., ZALF e.V. and Gut Wilmersdorf GbR; 2004. Available from: http://www.praxisversuche.de/index.php.

[35] Bachinger J, Reckling M, Stein-Bachinger K. N-budget calculator for legume grass-mixtures. Leibniz-Centre for Agricultural Landscape Research; 2013. Available

from: http://www.zalf.de/de/forschung/institute/lse/downloads/Documents/oekolandbau/saldorechner/Nbudget_calculator.xls.
[36] Peigné J, Messmer M, Aveline A, Berner A, Mäder P, Carcea M, et al. Wheat yield and quality as influenced by reduced tillage in organic farming. Organic Agriculture. 2014;4(1):1–13.
[37] Vakali C, Zaller JG, Köpke U. Reduced tillage effects on soil properties and growth of cereals and associated weeds under organic farming. Soil & Tillage Research. 2011;111:133–141.
[38] Berner A, Hildermann I, Fließbach A, Pfiffner L, Mäder P. Crop yield and soil fertility response to reduced tillage under organic management. Soil & Tillage Research. 2008;101:89–96.
[39] Emmerling C. Reduced and Conservation Tillage Effects on Soil Ecological Properties in an Organic Farming System. Biological Agriculture and Horticulture. 2007;24:363–377.
[40] Triplett Jr GB, Dick WA. No-Tillage Crop Production: A Revolution in Agriculture! Agronomy Journal. 2008;100:153–165.
[41] Gruber S, Möhring J, Claupein W. On the way towards conservation tillage-soil moisture and mineral nitrogen in a long-term field experiment in Germany. Soil & Tillage Research. 2011;115–116:80–89.
[42] Hamza M, Anderson W. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil & Tillage Research. 2005;82:121–145.
[43] Hofbauer M, Bloch R, Gerke HH, Bachinger J. Effekte des Ringschneidereinsatzes zur pfluglosen Bodenbearbeitung auf physikalische Eigenschaften sandiger Böden. In: Neuhoff D, Stumm C, Ziegler S, Rahmann G, Hamm U, Köpke U, editors. Beiträge zur 12. Wissenschaftstagung Ökologischer Landbau. Berlin, Germany: Köster Berlin; 2013. pp. 34–37.
[44] Mäder P, Berner A. Development of reduced tillage systems in organic farming in Europe. Renewable Agriculture and Food Systems. 2012;27(01):7–11.
[45] Bàrberi, P. Weed management in organic agriculture: are we addressing the right issues? Weed Research. 2002;42:177–193.
[46] Kolb LN, Gallandt ER. Weed management in organic cereals: advances and opportunities. Organic Agriculture. 2012;2(1):23–42.
[47] SMUL. Sächsische Landesanstalt für Landwirtschaft, editor. Umsetzung der Düngeverordnung: Hinweise und Richtwerte für die Praxis. Dresden; 2007. Available from: https://publikationen.sachsen.de/bdb/artikel/15242.
[48] Kay QON. Tripleurospermum Inodorum (L.) Schultz Bip. Journal of Ecology. 1994;82(3):681–697.
[49] Schmid H. Bodenbearbeitung im ökologischen Ackerbau ohne tiefes Pflügen. Justus-Liebig-Universität Gießen; 2011.
[50] Gattinger A, Fliessbach A. Rolle des Ökologischen Landbaus beim Klimawandel. In: Agrarsoziale Gesellschaft e V (ASG), editor. Klimaschutz- und Anpassungsstrategien in Landwirtschaft und ländlichem Raum. vol. 61. Göttingen; 2010.