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DOI: <https://doi.org/10.1016/j.fcr.2020.107736>

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ZORA URL: <https://doi.org/10.5167/uzh-193823>

Journal Article

Accepted Version

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Originally published at:

Wittwer, Raphaël A; van der Heijden, Marcel G A (2020). Cover crops as a tool to reduce reliance on intensive tillage and nitrogen fertilization in conventional arable cropping systems. *Field Crops Research*, 249:107736.

DOI: <https://doi.org/10.1016/j.fcr.2020.107736>

Cover crops as a tool to reduce reliance on intensive tillage and nitrogen fertilization in conventional arable cropping systems

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Highlights

- Nitrogen fertilization can be reduced after legume cover crops without compromising yield.
- Tillage intensity can be reduced only in combination with cover cropping.
- Weed control under reduced tillage is challenging, even with cover crops.
- Maize depleted nitrogen in absence of a legume cover crop.
- Aerial spectral imagery provided insight into crop growth dynamics.

Abstract

Cover crops are often recommended as a valuable practice to develop more sustainable cropping systems but, despite many benefits, their adoption in practice is still limited mainly because the effects on productivity and economic return are variable. Furthermore, it is still unclear under which combinations with other management practices (e.g. tillage, fertilization, weed control) cover crops can provide the highest paybacks.

Here we tested whether cover crops are a suitable management tool to reduce fertilizer input, tillage intensity and herbicide use in Swiss arable cropping systems. We compared the effects of four different cover crop treatments (fallow, radish, subterranean clover and hairy vetch) on maize at two fertilization levels combined with three levels of tillage intensity. To unravel the effects of cover crops on maize growth, we assessed vegetation dynamics using the Normalized Differential Vegetation Index (NDVI) from aerial spectral imagery.

Cover crops on average increased yields by 12% (+7% to +20%) and cover crop effects depended on tillage intensity, fertilization level and cover crop treatment for most of the assessed maize parameters. Best results were obtained with hairy vetch, which increased maize N uptake by 79 kg ha⁻¹ on average. As a consequence, at least combinations of two of the three targeted inputs (tillage, fertilization and herbicides) could be successfully reduced, e.g. tillage and fertilization under no tillage or tillage and herbicides under reduced tillage. Even under intensive tillage, both legume cover crops allowed a reduction of fertilization without compromising yield. Spectral imagery analysis showed that legume cover crops compensated for delayed N availability in reduced and no tillage systems and cover crops contributed to enhanced N uptake and crop growth later in the season.

We provide evidence that cover crop based cropping systems can be used to reduce synthetic inputs and tillage without compromising yield, thus presenting an example of ecological engineering. We highlight the importance of considering the whole set of management practices

44 when adopting cover cropping in order to maintain or increase productivity with reduced
45 anthropogenic inputs under conventional cropping.
46 **Keywords:** conservation agriculture; drone imagery; ecological intensification; maize; hairy
47 vetch

1 Introduction

The intensification of arable production have made a substantial contribution to increased world food production over the last 50 years (Tilman *et al.*, 2002). However, current agricultural practices have also given rise to environmental concerns regarding decreased biodiversity, reduced water quality, and degraded soil quality (Stoate *et al.*, 2001). Although the use of mineral fertilizers and pesticides has led to a considerable increase in productivity, arguably the main ecosystem service provided by agriculture, this has been at the cost of other regulating and supporting services provided by agro-ecosystems (Power, 2010). The internal regulation of nutrient cycles, the natural control of pests and diseases, and the abundance and diversity of soil organisms are often downregulated in intensively managed fields. As a result, high agricultural productivity becomes dependent on anthropogenic-synthetic inputs and is no longer sustainable in the long-term (Geiger *et al.*, 2010; Tsiafouli *et al.*, 2015).

Ideally, a sustainable system will maintain the right balance between external inputs and ecosystem service delivery, thus providing high productivity based on optimized internal regulatory processes and resilience of the system (Bender *et al.*, 2016). This goal could be achieved by including agricultural practices that promote regulating and supporting ecosystem services and preserving soil quality, also called ecological engineering.

One example of this is conservation agriculture (CA), which principles include reduced tillage, improved crop rotation, and permanent soil coverage (Teasdale *et al.*, 2007; Hobbs *et al.*, 2008; Doltra and Olesen, 2013). Although CA contributes to soil conservation, reduced consumption of fossil fuels, a reduced work load, and is widely propagated in the America's and Australia, adoption rates in Europe are still very low (Derpsch *et al.*, 2010; Kertész and Madarász, 2014; Casagrande *et al.*, 2016). The main reasons why CA is not widely adopted in Europe include the often more complex crop rotations (e.g. presence of ley), problems related to weed control, and delayed spring nutrient mineralization.

Another option to improve the sustainability of agricultural production is the use of cover crops. Cover crops are grown between two main crops and are a crucial element of CA systems to reach an appropriate soil coverage during fallow period as well as maintain productivity (Hartwig and Ammon, 2002; Pittelkow *et al.*, 2015; Marcillo and Miguez, 2017). Cover crops provide a range of ecosystem services, as they have been shown to protect soil against erosion, reduce the risk of surface and ground water pollution, improve soil structure, and promote soil biota (Dabney *et al.*, 2001; Kohl *et al.*, 2014; Schipanski *et al.*, 2014; Blanco-Canqui *et al.*, 2015). Moreover, cover crops play an important role in the management of nitrogen (N) within arable cropping systems, either by preventing leaching losses (non-legume species) (De Notaris *et al.*, 2018; Thapa *et al.*, 2018) or by providing additional N input through biological fixation (legume species) (Thorup-Kristensen *et al.*, 2003; Couédel *et al.*, 2018). Cereal-based systems, particularly maize, benefit greatly from additional N input by legume cover crops, as shown by several studies (Miguez and Bollero, 2005; Gabriel and Quemada, 2011; Liebman *et al.*, 2012; Tosti *et al.*, 2012; Komainda *et al.*, 2017).

All these benefits have been extensively described as well as the importance of direct cover crop management, e.g. sowing and termination date or termination techniques (Thorup-Kristensen and Dresboll, 2010; Alonso-Ayuso *et al.*, 2014; Radicetti *et al.*, 2016; Osipitan *et al.*, 2019). Cover crops have also been shown to be important when conservation tillage is applied or to reduce N applications. However, few studies have investigated to which extent cover crop based agro-ecosystem services are influenced by the combination of these management practices or, more generally, perform within defined cropping systems. (Wittwer *et al.*, 2017). Both tillage and fertilization greatly influence soil properties and processes, such as organic matter mineralization (Balesdent *et al.*, 1990; Kandeler *et al.*, 1999) and weed abundance, which in turn influence crop nutrition and productivity (Shelton *et al.*, 2017). For example, it is still unclear if and to which extent cover crops can reduce the reliance on fertilizers under different tillage intensities without impairing crop yield. Moreover, earlier

studies reported that legume cover crops can fix more than 100 kg N ha⁻¹ year⁻¹, but it is still difficult to predict how much of this N can be effectively used by the following crop (Thorup-Kristensen *et al.*, 2003; Büchi *et al.*, 2015). Additionally, cover crops could suppress weeds and thus have the potential to reduce tillage and herbicide use, especially if cover crops can be easily managed before the main crop is planted (Dorn *et al.*, 2015). Thus, it is increasingly important to gain a clearer understanding of the interactions between cover cropping and other field management practices, such as tillage intensity or fertilization in an effort to optimize cover crop effects on productivity and profitability, and thereby achieve a wider adoption of this practice by farmers as a mean of ecological intensification (Roesch-McNally *et al.*, 2017).

Consequently, this study focuses on the interactions between tillage intensity, N fertilization and cover cropping in Swiss conventional arable crop production. Two replicated field experiments were conducted during the years 2012-2014 and 2013-2015 with a crop sequence of winter wheat, cover crops, and maize in Eastern Switzerland. The effect of three different cover crops (hairy vetch (*Vicia villosa*), oilseed radish (*Raphanus sativus*) and subterranean clover (*Trifolium subterraneum*)) were compared to fallow combined with three levels of tillage intensity coupled with weed control strategy (intensive tillage with herbicides, reduced tillage without herbicides, and no tillage with herbicides) and two levels of N fertilization.

The main aim of the study was to evaluate the extent to which the use of cover crops can decrease dependency on intensive tillage, synthetic N fertilization, and herbicides. Thus, based on the assumptions that:

- i) cover crops help to reduce tillage intensity,
- ii) additional N input provided by legume cover crops can partly replace the addition of synthetic N fertilizer, and
- iii) the combination of cover cropping and reduced tillage allows a reduced use of herbicides,

we aimed to identify best combinations of the investigated management practices to sustain productivity but reduce anthropogenic inputs.

2 Materials and methods

2.1 Study site and field experiments

Two field experiments were conducted during the years 2012-14 (Experiment I) and 2013-15 (Experiment II) at the research station Agroscope in Tänikon, Switzerland (47°28'50'' N, 8°54'25'' E, 537 m a.s.l.). The top soil of both experiments is classified as sandy loam, containing on average 21% clay, 35% silt and 44% sand, with 2.1 % organic carbon content, 0.23 % total nitrogen content, and it had a pH (H₂O) of 7. The long-term (1981-2010) mean annual temperature is 8.7°C, while annual precipitation averages 1184 mm. Weather conditions in the experimental years did not substantially deviate from the long-term averages (2014: 10°C and 1113 mm, 2015: 9.8°C and 927 mm). However, a slight drought period occurred from July to September 2015 (Supplementary Figure S1).

The two experiments have exactly the same experimental design and the only difference is the start date, where experiment II starts one year later. This was done to obtain a more robust understanding of the treatment effects across years. The two experiments (I and II) were arranged in a strip-split-plot design with four replicates. Factor I (main plots, only applied to maize) was three levels of tillage intensity coupled with weed management strategy: 1) intensive tillage (IT) by mouldboard ploughing and use of post-emergence herbicides, 2) no-tillage (NT) with the use of glyphosate and post-emergence herbicides, and 3) reduced tillage (RT) by shallow non-inversion tillage and mechanical weed control in maize. Factor II (subplot CC) consisted of four different cover crop treatments: 1) oilseed radish (cv. Pegletta) as a fast growing non-legume cover crop (RS), 2) hairy vetch (cv. Hungvillosa) as a high biomass overwintering legume cover crop (VV), 3) subterranean clover (cv. Campeda) as a self-re-

seeding specie, which was already undersown in the previous crop (winter wheat) as living mulch and should also act as cover crop before maize (TS), and 4) fallow (as control). Although, the aim was that subterranean clover can re-establish by itself, it was re-sown after winter wheat harvest because the re-seeding rate was too low for appropriate soil coverage. Factor III (subplot F) was ammonium nitrate application to the main crops either at the norm (normN) or half rate (halfN) of what is recommended to farmers in Switzerland (Flisch *et al.*, 2009). The combination of these three factors resulted in 24 treatment-combinations and 96 plots per experiment. The size of the main plot (tillage) was 384 m² (12x32m) and the smallest plot size was 48 m² (6x8m) (Figure 1).

2.2 Crop management

The two experiments consisted of a winter wheat - cover crop - maize crop sequence. In the years preceding the experiments, the fields were managed conventionally and annually ploughed 20-25 cm deep. Forage pea (*Pisum sativum* subsp. *arvense*) was grown prior to the start of the experiments, and, after ploughing the experimental field, winter wheat (*Triticum aestivum* L. cv. 'CH Claro') was sown early October (5.20.12 in Exp. I and 3.10.13 in Exp. II) either as pure crop (control, RS and VV cover crop treatments) or intercropped with subterranean clover (TS treatment). Weed control in wheat was performed by herbicide application in the pure wheat plots (control, RS and VV cover crop treatments), whereas no weed control was performed in the intercropped wheat (TS treatment). The normN fertilization plots received a total of 140 kg N ha⁻¹ in three applications (70/30/40), and the halfN fertilization plots a total of 70 kg N ha⁻¹ in two applications (45/25). The results from the wheat-clover intercropping treatment have already been published (Radicetti *et al.*, 2018), and in this study we focus on the effect of cover cropping, coupled with tillage and fertilization, on maize production.

175 After wheat harvest (3.8.13 in Exp. I and 25.7.14 in Exp. II), the straw was removed from the
176 plots and all three winter cover crops (RS, VV, and TS) were sown (21.8.13 in Exp. I and 7.8.14
177 in Exp. II) after a shallow stubble cultivation (rotary cultivator at 5cm soil depth, also in the
178 control plots). Cover crops and weeds in control plots were terminated the next spring by either
179 tillage (IT and RT treatments, 18.5.14 in Exp. I and 13.5.15 in Exp. II) or by applying 1.44 kg
180 ha⁻¹ (active ingredient) glyphosate in the NT treatment (30.4.14 in Exp. I and 29.4.15 in Exp.
181 II). The IT treatment consisted of mouldboard ploughing at 20cm soil depth and a seed bed
182 preparation with a rotary harrow at 5cm soil depth. The RT treatment was performed with a
183 precision cultivator (Weco-dyn, Friedrich Wenz GmbH) in three passes: the first two passes at
184 2-3 cm and the third one at 5-6 cm soil depth. Cover crop biomass was mulched with a flail
185 mower prior to tillage operations in the IT and RT treatments.

186 Maize (*Zea mays* L. cv. ‘ LG 30.222’) was sown at the end of May (22.5.14 in Exp. I and
187 28.5.15 in Exp. II) with a row distance of 0.75 m and combined with an underfoot starter-
188 fertilization of 30 kg N ha⁻¹ in both fertilization treatments. The normN plots received an
189 additional 60 kg N ha⁻¹ (90 kg N in total) and the halfN plots additional 15 kg N ha⁻¹ (45 kg N
190 in total) at maize growth stage BBCH15-17. Weeds during maize growth were controlled by
191 herbicides in the IT and NT treatments, but were controlled mechanically by hoeing two times
192 in the RT treatment. Primary tillage and post-emergence weed control were combined in one
193 factor as they are both integrated part of weeding strategies. Indeed, herbicides are commonly
194 applied in conventional systems and glyphosate application is still predominating in no tillage
195 systems. The use of reduced tillage without herbicides was therefore designed in one hand to
196 reduce tillage intensity and to avoid the use of glyphosate as well as post-emergence herbicides.
197 Thus, the two factor-combinations RT/TS/50N and RT/TS/100N did not receive any herbicide
198 during the experimental period and the other RT treatments no herbicides in maize only. Maize
199 was harvested as whole plant (9.10.14 in Exp. I and 8.10.15 in Exp. II) and as grain (30.10.14

in Exp. I and 28.10.15 in Exp. II). Additional information regarding field operations (dates, amount applied, and machinery) can be found in supplementary Table S1.

2.3 Measurements

Cover crop growth was monitored by evaluating the percentage of soil covered by cover crop species and weeds at 20, 30 and 60 days after sowing (DAS). Two pictures per plot were taken at 180cm height, covering 1 m² ground surface, using a bipod stand. Total plant soil cover was then determined with the program ASSESS 2.0 (Lamari, 2008) based on colour saturation. The percentage of soil covered by cover crops versus weeds was then determined visually based on the pictures. Additionally, cover crop and weed biomass were determined before termination in spring by cutting the plants 1 cm above the soil surface within two randomly placed quadrants (50cm x 50cm) per subplot. Weed and cover crop species were sorted for each sample before dry weight determination.

In maize, weed density and biomass were assessed at the end of maize flowering (BBCH69) to determine weed pressure in four quadrants (50cm x 50cm) per subplot. Mean values – for cover, density, and biomass data – were calculated for each subplot and used for the analyses.

Maize biomass (whole plant) and grain yield were determined by harvesting two rows in each plot (7 m length) with adapted plot-sized combine harvesters. Biomass and grain weights were directly measured by the harvesters and a subsample was collected per plot for dry matter and nutrient content determination. Dry matter content was determined by oven-drying plant material (cover crops, weeds, maize biomass and grain) at 105°C for 30 hours to adjust yield and biomass data to t dry matter (DM) ha⁻¹. Plant materials for nutrient analyses were oven-dried at 60°C and finely ground. The N and C concentrations of cover crop biomass as well as N concentration of maize biomass and grain were then determined using elemental analysis by the Dumas method (Dumas, 1831).

To assess the impact of the treatment combinations on the N status of the different cropping systems, we calculated the overall N balance as the difference between the total amount of N input and the amount of N exported at harvest. Here, N input is the combination between the N applied as mineral fertilizer (Nfert) and an estimation of N fixed by the legume cover crops (Nfix). Nfix was calculated as the N content in cover crops at termination multiplied by the percentage of N derived from the atmosphere (%Nd_{fa}) using values obtained by Büchi et al. (2015) for subterranean clover and hairy vetch in Switzerland. A positive N balance reflects an N surplus in the system and a negative balance implies that soil N was depleted.

Additionally, the N Nutrition Index (NNI) was computed for each plot as the ratio between measured maize biomass N concentration and the critical N concentration (N_{crit.}) calculated after Plénet and Lemaire (1999):

$$N_{crit.} = 3.40 * (biomass)^{-0.37} \quad (1)$$

In order to assess the contribution of cover crops to maize N nutrition, a cover crop N effect (N_{effCC}) was calculated (Tosti *et al.*, 2012):

$$N_{effCC,i} = N_{uptCC,i} - N_{uptCtr} \quad (2)$$

where N_{uptCC,i} is the N uptake of the main crop after a cover crop treatment and N_{uptCtr} is the N uptake of the main crop after the control treatment without cover crops. N_{effCC} values were calculated separately for the normN and halfN treatments. Additionally, the effect of N fertilization was calculated for the control plots by subtracting the N uptake of the halfN to the N uptake of the normN control plots for each tillage treatments.

Maize growth over the whole vegetation period was additionally monitored in experiment II (2015) with the help of the Normalized Differential Vegetation Index (NDVI) obtained from unmanned aerial vehicle (UAV) imagery. NDVI is a well-recognized vegetation index (Tucker, 1979) that gives information about the status of a crop and is calculated based on the red and near-infrared (NIR) reflectance values of a crop canopy as follow:

$$NDVI = (NIR - red) / (NIR + red) \quad (3)$$

The experimental field was regularly monitored with a NIR modified camera (Canon S110 NIR, 12 MP), mounted on an automated fixed-wings UAV (eBee AG, senseFly), acquiring image data in the near-infrared (850nm), red (625nm), and green (550nm) spectral band at an average ground resolution of 2cm per pixel. NDVI values at the plot level were then obtained for each flight by extracting the mean pixel value from NDVI index-maps created with the software PostflightTerra 3D (Pix4D, version 4.0.104) (Figure 1). Reflectance values for each pixels were calibrated with the camera settings by the software but no further radiometric calibration were performed. However, all flights were conducted under sunny conditions (without clouds) between 12pm and 2pm to reduce the impact of varying light conditions (Rasmussen *et al.*, 2016). Maize growth curves were then obtained for each plot by fitting data with the loess function (span=0.5) (Cleveland and Devlin, 1988) and the following physiological parameters were then extracted for growth dynamics analyses (Fig. 2):

- MaxNDVI: the maximal NDVI value across the vegetation period
- Time integrated NDVI (TIN): daily (interpolated) integration of NDVI for the entire duration of the vegetation period, also split at 76 DAS (half of the maize vegetation period) into the growth period (TIN_{growth}) and the senescence period (TIN_{sen})
- Growth rate (GRate): mean daily growth rate until 76 DAS (half of the maize vegetation period).

2.4 Statistical analysis

Statistical analyses were all performed using R (R Core Team, 2014). Variance analyses on the assessed variables were performed using a strip-split-plot design with “tillage” (IT, NT, RT) as the main plot, and “cover crop” (control, RS, TS, VV) and “fertilization” (normN, halfN) as crossed-subplot in an ANOVA using linear mixed effects models (Kuznetsova *et al.*, 2015). The terms “experiment” and “replicate blocks within experiment” were included first in the model to account for their variation. Tillage, cover crop, and fertilization as well as their

interactions were considered as fixed effects. Additionally, and because the experiments (I and II) were performed in two years (2014 and 2015), the interactions of experiment (year) and the three main factors were also included in the model. To identify suitable combination of cover crops with tillage and fertilization, all treatments were additionally contrasted against the reference treatment with intensive tillage, norm fertilization and no cover crop using the R package lsmeans (Lenth, 2018). Contrasts were also used to test if the N balances differ from 0 (neutral N balance). Data were square root transformed when residual plots revealed deviation from normality: that is for N content and C/N ratio of cover crops, weed biomass in cover crops and both weed density measures in maize. For a better interpretation of the results these data were back-transformed in the figures and tables.

3 Results

3.1 Cover crop performance

All three cover crops established satisfactorily, with over 65 % soil cover 60 days after sowing and significantly suppressed weeds compared to the control treatment (Table 1, Supplementary Table S2). Hairy vetch produced the highest biomass, with on average over 3 t ha⁻¹ aboveground DM biomass, followed by subterranean clover with over 1 t ha⁻¹. Both are overwintering species in contrast to oilseed radish, which was already terminated by frost during winter and left less than 1 t ha⁻¹ biomass at termination in spring. Oilseed radish was still able to suppress weeds as well as hairy vetch until spring, whereas subterranean clover was not as efficient (Figure 3). This could be partly due to the slower growth of clover in autumn. The cover crops differed significantly in their N content and C/N ratio. Hairy vetch had the highest aboveground N content (over 140 kg N ha⁻¹) and the lowest C/N ratio (10), followed by subterranean clover (32 kg N ha⁻¹, C/N ratio of 15) and radish (8 kg N ha⁻¹, C/N ratio of 30) (Supplementary Table S2). Overall, cover crop growth did not differ among the main plots and thus left similar conditions

before differential tillage was applied to maize. More importantly, the two fertilization levels applied to the previous wheat crop had only minor effects on cover crop performance with overall a significant but slightly higher cover crop biomass after half fertilization in wheat (+ 0.12 t ha⁻¹). This was mainly driven by a higher biomass for the legume cover crops under half fertilization (note that fertilization was applied to wheat but not directly applied to the cover crops). However, absolute differences were marginal.

The amount of aboveground atmospheric fixed N added by the legume cover crops was estimated at 125 kg N ha⁻¹ for hairy vetch and 19 kg N ha⁻¹ for subterranean clover (Supplementary Table S2). This large difference was due to the differences in biomass production and differences in the %Ndfa estimation factor, which was 88% for vetch and 61% for subterranean clover.

3.2 Weed pressure

Although weeds were successfully controlled during the cover cropping period, cover crops generally had little impact on weed pressure in maize. The largest and most significant differences were observed on weed biomass at maize flowering between the different tillage and weed control strategies (Table 1, Figure 3). In the reduced tillage treatment, with only mechanical weed control, weeds could not be fully controlled. In contrast weed biomass was very low in the intensive tillage treatment and in the NT treatment, where glyphosate was applied, in combination with post-emergence herbicides to control weeds.

Although no herbicides were applied in the TS treatment in the previous crop (wheat) and TS did not suppressed weeds as well as RS and VV during the cover crop period, this did not result in higher weed pressure in maize compared to the other cover crop treatments (Figure 3). N fertilization had no impact on weed pressure in maize and is therefore not displayed in Figure 3.

3.3 Maize productivity

All three treatment factors (e.g. fertilization, tillage and cover crop) significantly influenced maize biomass and grain yield (Table 1). The highest maize grain yield was obtained after intensive tillage (9.8 t DM ha⁻¹ averaged across the treatments), and it was slightly but not significantly lower under no tillage (-10 %, 8.9 t DM ha⁻¹), and significantly lower after reduced tillage without herbicide (-22 %, 7.6 t DM ha⁻¹). Averaged across treatments, the norm N fertilization rate increased grain yield by 0.75 t DM ha⁻¹ compared to half fertilization. Lastly, all three cover crop treatments significantly increased grain yield compared to fallow (8.0 t DM ha⁻¹). The yield gain after cover crops was moderate after oilseed radish (+7 %, 8.5 t DM ha⁻¹) and subterranean clover (+11 %, 8.9 t DM ha⁻¹), and highest after hairy vetch (+ 20%, 9.6 t DM ha⁻¹).

Interestingly, significant interactions between cover crop and tillage, as well as cover crop and fertilization were observed (Table 1) indicating that the effect of the cover crops on maize yield depended on tillage treatment and fertilization treatment. For instance, consistent positive effects of all cover crops were observed under no tillage compared to the fallow treatment (RS: +12%, TS: +14%, VV: +19%), whereas only the two legume cover crop treatments increased yield under IT (TS: +9% and VV: +10%) and only hairy vetch significantly increased yield under RT (VV: +36%). Moreover, no significant yield differences were observed between half and norm fertilization within the legume cover crops (TS and VV), whereas significantly less yield was obtained with half fertilization after fallow (-10%) or radish (-13%). Finally, all treatment were contrasted against the reference system with intensive tillage, norm fertilization and no cover crop. Several cover crop combinations with no tillage and reduced tillage and with half fertilization under no tillage were not significantly different (Figure 4). This indicate that inputs (e.g. fertilization or energy for tillage) could be successfully reduced but yield level was maintained.

Overall, yield level corresponded to mean yield expectation for Switzerland (10 t ha^{-1}) but was higher in Exp. I (2014) than in Exp. II (2015). The reduced yield in 2015 could be partly explained by the lower precipitation amount in July and August 2015 (Supplementary Figure S1), which could have negatively influenced N availability. The interaction of year with fertilization also points in this direction (Supplementary Figure S2). However, tillage and cover crop effects did not vary between Exp. I and Exp. II as revealed by the absence of a significant interaction term between year and tillage or year and cover crop treatment.

3.4 Maize nutrition and growth

Similar to the yield results, the N uptake of maize was significantly influenced by tillage, cover crop and fertilization as well as the interaction between cover crop and tillage (Table 1, 2). The highest N uptake was observed under intensive tillage ($194 \text{ kg ha}^{-1} \pm 12 \text{ ci}$), was not significantly lower under no tillage ($182 \text{ kg ha}^{-1} \pm 11 \text{ ci}$) but significantly lower under reduced tillage ($145 \text{ kg ha}^{-1} \pm 12 \text{ ci}$). Across all tillage and cover crop treatments, norm fertilization increased N uptake by 32 kg ha^{-1} . All cover crops also significantly increased maize N uptake compared to fallow ($142 \text{ kg ha}^{-1} \pm 10 \text{ ci}$) and differed from each other with increasing effect from radish to hairy vetch (RS: $157 \text{ kg ha}^{-1} \pm 11 \text{ ci}$, TS: $175 \text{ kg ha}^{-1} \pm 14 \text{ ci}$, VV: $221 \text{ kg ha}^{-1} \pm 12 \text{ ci}$).

In order to assess the contribution of cover crops to maize N uptake, a cover crop N effect (NeffCC) was calculated (see equation (2) in the methods). NeffCC was significantly different among tillage and cover crop treatments but not among fertilization treatments (Table 1, 2). Averaged across all tillage systems and compared to bare fallow, radish increased N uptake by 15 kg ha^{-1} , subterranean clover by 33 kg ha^{-1} and vetch by 79 kg ha^{-1} . In comparison, adding 45 kg N as mineral fertilizer increased maize N uptake by 40 kg ha^{-1} in the control plots without cover crops, regardless of tillage intensity. However, the overall cover crop effect was highest

under intensive tillage ($57 \text{ kg ha}^{-1} \pm 10 \text{ ci}$) and significantly lower under no and reduced tillage (NT: $37 \text{ kg ha}^{-1} \pm 7 \text{ ci}$, RT: $33 \text{ kg ha}^{-1} \pm 11 \text{ ci}$).

The N Nutrition Index (NNI) for maize also revealed the importance of increased N uptake, as only the treatments which attained an N uptake of about 215 kg N ha^{-1} reached an NNI of 1 indicating no N limitation (Supplementary Figure S3). This was the case for almost all hairy vetch plots (except under RT 50N) and maize following subterranean clover but with full fertilization (except under RT) (Table 2).

To better understand the temporal dynamics behind treatment effects, maize growth was monitored during the growing season in experiment II in 2015 based on NDVI from UAV imagery (Figure 5). The tillage effect on early crop growth could be detected, as indicated by the phenological parameter growth rate and max NDVI, which were significantly lower under NT and RT than IT. Cover crops, and especially hairy vetch, positively influenced maize growth throughout the growing season. This effect was most pronounced under reduced tillage and intensive tillage early in the season (Figure 5, panel a, b, e, f) when treatments with hairy vetch had enhanced maxNDVI, growth rate and TIN growth levels, more strongly under IT and RT than NT. The positive effect of hairy vetch also appeared under no tillage later on (Figure 5, panel c, d), as higher TINsen values were obtained under no tillage and the factor tillage was not anymore significant (Table 1, Supplementary Figure S4).

3.5 N balance

When assessing the impact of cover crops on overall N fluxes, we found that the effects were similar among the tillage and fertilization treatments, with a positive N balance after hairy vetch ($+42 \pm 14 \text{ ci}$) and negative values for the other cover crop treatments (Control: $-35 \pm 14 \text{ ci}$, RS: $-47 \pm 8 \text{ ci}$, TS: $-36 \pm 11 \text{ ci}$) indicating that in those treatments maize removed more N from the soil compared to what was added. The higher N input from hairy vetch led to neutral N balance under half fertilization (except under RT) and a significantly positive N balance under norm N

fertilization. In general, more neutral N balances were obtained under RT, mostly with full fertilization, in contrast to either negative or positive N balances under IT and NT (Figure 6).

4 Discussion

It is known that cover crops can contribute to more sustainable cropping systems (Olesen *et al.*, 2007; Schipanski *et al.*, 2014; Giuliano *et al.*, 2016). Although positive effects of cover crops on crop yield have been widely described (Tonitto *et al.*, 2006; Marcillo and Miguez, 2017) there is still poor adoption by farmers at a larger scale (Panagos *et al.*, 2015; Seifert *et al.*, 2018), even if various national and regional incentives have recently initiated a positive trend and higher integration of cover crops into rotations (Storr *et al.*, 2019). Still, one key aspect to increase the use of cover crops would be to improve the return on invest for farmers by optimizing cover crop based systems in order to increase profitability. This can be achieved either by reducing synthetic inputs (e.g. fertilizers, pesticides) and energy use (e.g. fuel for tillage) or by significantly increasing yield, also called ecological intensification. Moreover, for farmers it is important to know under which conditions and with which field operations cover crops are most beneficial to fulfill these expectations.

In our study, we focused on conventional cereal based cropping systems, which are one of the most widespread agricultural production systems in Europe or North America (FAO, 2019). Cereal-based systems are characterized by high inputs of fertilizers and pesticides, and, at least in Europe, relatively high tillage intensity. Finding ecological cropping practices that can substitute a certain amount of inputs while maintaining productivity, also called ecological engineering, is therefore needed to design more sustainable cropping systems (Bender *et al.*, 2016). We were particularly interested in understanding to which extent other field practices influence cover crop effects, and therefore finding most promising combinations of cover cropping with tillage intensity, N fertilization and weed control strategy.

Our results underline earlier findings that introducing cover crops allows a reduction of tillage intensity (Mirsky *et al.*, 2012; Wittwer *et al.*, 2017; Büchi *et al.*, 2018), as similar yield could be achieved under no and reduced tillage compared to our reference treatment with intensive tillage, full fertilization and no cover crop. We also found that legume cover crops can deliver substantial amounts of N to the following crop, achieving similar yields even when N fertilization was halved (Marcillo and Miguez, 2017). The addition of hairy vetch, a high biomass legume cover crop, enhanced maize N uptake substantially (e.g. up to 109 kg N ha⁻¹ additional uptake). Such effects were already observed in other studies (Tosti *et al.*, 2012) but it was still not well known that such results also apply for systems with reduced or no tillage where mineralization rate are expected to be lower and residues left at the surface. Moreover, the obtained results were consistent across different years, showing that these results were repeatable and were not much influenced by inter-annual climatic variations at our experimental site. Note that precipitations are not a main limiting factor in this region and that outcome could be different in water limited regions.

Our results also indicate that N input by legume cover crops more positively impacted N balance than mineral fertilization as neutral balances were achieved with hairy vetch under half fertilization in contrast to full fertilization but no cover crop. Interestingly, the N balance for maize was only positive in treatments after hairy vetch as a cover crop, while in all other treatments the N balance was negative, indicating that maize removed more nitrogen from the soil compared to what was added. However, it is also important to note that a positive N balance can also indicate a higher risk of N leaching, because N surplus and, in case of mineralisation, enhanced soil N availability could potentially be lost if not synchronized with crop needs. On the other hand, one advantage of legume derived N is that it is generally less prone to leaching than mineral N, as organic N is better retained in the soil (Crews and Peoples, 2005; Tosti *et al.*, 2019). Thus even if an important fraction is not recovered in the crop (Almeida Acosta *et al.*, 2011), it has a lower potential to be lost in the environment in contrast to mineral fertilizers

(Hansen *et al.*, 2019). Moreover, it was shown that high quality residues of cover crops can support carbon- and nutrient-cycling management through litter feedbacks on decomposition within cropping systems (Barel *et al.*, 2018). Our results demonstrate that reducing N fertilization coupled with a high biomass legume cover crop can achieve a neutral N balance and thus sustain crop growth and N stocks in the system. The higher N balance for the treatment combination with reduced tillage and hairy vetch as cover crop (RT VV) resulted in an N surplus but this could be partly explained through the higher weed biomass in this treatment that probably has taken up a substantial amount of N, which was not accounted in the N balance calculation.

Another important aspect to consider is the interest to reduce the global warming potential of cropping systems (e.g. reduce greenhouse gas emissions). Synthetic fertiliser use is one of the most important factors contributing to the global warming potential in Switzerland and Western Europe (Prechsl *et al.*, 2017) because the production of synthetic nitrogen requires substantial amounts of energy (Woods *et al.*, 2010). Moreover, N fertilization can significantly contribute to greenhouse gas emissions, especially through the production of the greenhouse gas nitrous oxide (Skinner *et al.*, 2019). In contrast, nitrous oxide emissions derived from legume cover crops were shown to be low (Peyrard *et al.*, 2016). Thus, the observation that nitrogen fixing cover crops can maintain yield at the same level, but with 50% less nitrogen input is a promising observation which can help to reduce the contribution of arable cropping systems to global warming.

Earlier studies used drones and UAV imagery to monitor the development of crop yield and the presence of nutrient deficiencies in crops at field scale (Maresma *et al.*, 2016; Rasmussen *et al.*, 2016). So far, UAV imagery has, to our knowledge, not been used to monitor the temporary effects of cover crops or differences between tillage intensities. We used the vegetation index NDVI as a proxy for crop growth and N uptake, which provided new insight behind the temporal dynamic of cover crop effects under different tillage intensities. Overall, tillage mostly

influenced early maize growth whereas the use of cover crops before maize had a significant impact throughout the vegetation period. Based on the calculated phenological parameters, legume cover crops could compensate for delayed N availability in reduced and no tillage systems (e.g. Grate, maxNDVI), prolonged N uptake and crop growth later in the season (e.g. TIN, TINsen) and also compensated for reduced N fertilization. Based on these phenological parameters, we also found that N availability from legume cover crops is greater when incorporated through tillage (e.g. in the tilled treatments) but also becomes available under no tillage later in the season. Generally, N release from buried plant residues is faster than surface placed residues, and the N concentration and C/N ratio of the initial biomass are determinants for N release kinetic (Justes *et al.*, 2009; Jahanzad *et al.*, 2016). Further research could explore how to adapt fertilization strategies in combination with legume cover crops to best fit crop needs under reduced and no tillage. Finally, all calculated phenological indexes (maxNDVI, Time Integrated NDVI and GrowthRate) significantly correlated with maize biomass and N uptake (Supplementary Figure S4). This also shows the potential of this approach to predict yield and N uptake over larger areas and therefore potentially be used to adapt fertilization depending on crop needs (Maresma *et al.*, 2016; Nuijten *et al.*, 2019).

By combining tillage and weed management we also aimed at reducing herbicide use, particularly under conservation tillage, as the application of herbicides is more and more criticized in society. Our results shows that cover crops did not significantly help to reduce weed pressure in the following maize crop. Although cover crops have the potential to keep weed pressure low, effects are very variable and depend even more on long-term management and initial weed pressure (Osipitan *et al.*, 2019; Reimer *et al.*, 2019). The only treatment with reduced use of herbicides that could maintain yield was the combination of reduced tillage with hairy vetch and norm fertilization. The higher N input by hairy vetch have probably alleviated the competition for nutrients by weeds in this treatment but it remains uncertain if this is a viable practice in the long-term.

In summary, this study demonstrated that best results on productivity were obtained with hairy vetch as a cover crop similarly to Liebman et al. (2018). Moreover, at least combinations of two of the three targeted inputs could be successfully reduced, e.g. tillage and fertilization under no tillage or tillage and herbicides under reduced tillage. Even under intensive tillage, both legume cover crops allowed a reduction of fertilization without compromising yield. However we did not look at long-term effects of having repeated use of legumes as cover crops. Within the same experiment we have found that legume species have the potential to harbor important pest and disease as shown for nematodes (Schmidt *et al.*, 2017) and for *Fusarium* fungi (Walder *et al.*, 2017; Šišić *et al.*, 2018). Thus, their repeated use should be planned with caution. On the other hand, these risks as well as the amount of N delivered by cover crops could be managed by using mixtures of species and make use of their associated multiple services (Amosse *et al.*, 2015; Tribouillois *et al.*, 2015; Finney *et al.*, 2017; Couëdel *et al.*, 2018).

5 Conclusions

This study demonstrates that legume cover crops can be used to partly replace fertiliser inputs without compromising yield under intensive and no tillage, and thus confirms that cover cropping has the ability to facilitate conservation agriculture and more extensive cropping practices. Compared to intensive tillage, full fertilisation and herbicide use, similar yields were obtained when either tillage intensity and/or fertilization were reduced in combination with a legume cover crop. Thus, cover crops not only can be used to reduce nutrient leaching and protect soil against erosion, they can also help to reduce fertiliser input and tillage while maintaining typical productivity levels. Cover crops were not able to sufficiently control weeds under reduced tillage and without herbicide but, here again, similar yield could be obtained when N input from fertilization and legume cover crop was sufficient to alleviate negative impact of increased weed pressure.

Overall, this work demonstrates that cover crops are a suitable tool for ecological engineering, but we recommend that farmers and farmer advisors consider the whole set of cropping practices when adopting specific cover crops in order to maintain or increase productivity but reduce inputs needs and costs.

Acknowledgements

We thank Werner Jossi for excellent practical support in setting up the experiment and we would like to gratefully thank Grégoire Tombez for his help to implement UAV technology and analyses for this study and for field work. This work was financed by the European Union FP7 Project n.289277: OSCAR (Optimising Subsidiary Crop Applications in Rotations) and Agroscope.

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788 **Table 1: Statistical ANOVA output demonstrating the effects of the main factors experiment (year), tillage, cover crop and fertilisation and their**
789 **interaction terms on the assessed variables in maize. $F_{(df1,df2)}$ values (df1: numerator degrees of freedom; df2: denominator degrees of freedom) and**
790 **significance level (ns: non-significant; * $p<0.05$; ** $p<0.01$; *** $p<0.001$). NNI = Nitrogen Nutrition Index; NeffCC = N effect from cover crops; max NDVI**
791 **= maximal NDVI value across the growing season; Time integrated NDVI (TIN): daily (interpolated) integration of NDVI for the entire duration of the**
792 **vegetation period; Growth rate (GRate): mean daily growth rate until half growing season (76 days after sowing).**

Variables	Factors											
	Exp	Exp:Block	Tillage (T)	Cover crop (CC)	Fertilization (F)	T x CC	CC x F	T x F	T x CC x F	Year x T	Year x CC	Year x F
Cover crop												
Weed cover 60 DAS	ns	ns	ns	210.4 _(3,60) ***	ns	ns	4.3 _(3,63) **	ns	ns	ns	7.0 _(3,60) ***	ns
Weed biomass spring	11.3 _(1,12) **	ns	ns	143.5 _(3,60) ***	6.8 _(1,20) *	ns	4.5 _(3,63) **	ns	ns	ns	19.8 _(3,60) ***	ns
Cover crop cover 60 DAS	6.8 _(1,12) *	ns	ns	29.4 _(3,40) ***	8.3 _(1,20) **	ns	11.1 _(2,42) ***	6.8 _(2,20) **	ns	ns	10.1 _(2,40) ***	8.0 _(1,20) *
Cover crop biomass spring	ns	ns	ns	139.6 _(2,40) ***	4.9 _(1,20) *	ns	ns	ns	ns	ns	ns	ns
Cover crop N content	ns	ns	ns	236.6 _(2,40) ***	ns	ns	ns	ns	ns	ns	ns	ns
Cover crop C/N ratio	ns	ns	ns	293.6 _(2,40) ***	ns	ns	4.8 _(2,42) *	ns	ns	ns	24.8 _(2,40) ***	ns
Cover crop Ndfa	ns	ns	ns	239.0 _(2,20) ***	ns	ns	ns	ns	ns	ns	ns	ns
Maize												
Weed density after weed control	ns	ns	6.9 _(2,12) *	ns	ns	ns	ns	ns	ns	ns	ns	ns
Weed biomass after weed control	ns	ns	28.4 _(2,12) ***	ns	ns	ns	ns	ns	ns	15.9 _(2,12) ***	ns	ns
Biomass	25.5 _(1,12) ***	ns	17.7 _(2,12) ***	50.0 _(3,60) ***	75.8 _(1,20) ***	8.3 _(6,60) ***	5.7 _(3,63) **	ns	ns	ns	ns	7.2 _(1,20) *
Grain yield	4.8 _(1,12) *	ns	10.3 _(2,12) **	25.9 _(3,60) ***	42.8 _(1,20) ***	3.5 _(6,60) **	2.9 _(3,63) *	ns	ns	ns	ns	5.7 _(1,20) *
N uptake	22.1 _(1,12) ***	ns	27.2 _(2,12) ***	131.8 _(3,60) ***	253.4 _(1,20) ***	7.5 _(6,60) ***	ns	ns	2.8 _(6,63) *	ns	ns	28.3 _(1,20) ***
NNI	8.8 _(1,12) *	ns	39.3 _(2,12) ***	132.7 _(3,60) ***	250.8 _(1,20) ***	3.9 _(6,60) **	ns	ns	ns	ns	ns	21.3 _(1,20) ***
NeffCC	13.5 _(1,12) **	ns	17.1 _(2,12) ***	95.4 _(2,40) ***	ns	6.9 _(2,40) ***	ns	ns	4.1 _(4,42) **	ns	ns	ns
N balance	5.6 _(1,12) *	ns	13.1 _(2,12) ***	83.2 _(3,60) ***	79.8 _(1,20) ***	ns	ns	ns	3.0 _(6,63) *	ns	ns	10.2 _(1,20) ***
Maize NDVI (only Experiment II)												
max NDVI	-	ns	14.9 _(2,6) **	38.5 _(3,27) ***	42.3 _(1,9) ***	3.5 _(6,27) *	3.3 _(3,27) *	ns	ns	-	-	-
Growth rate (GRate)	-	ns	13.1 _(2,6) **	12.9 _(3,27) ***	22.8 _(1,9) **	3.6 _(6,27) **	3.7 _(3,27) *	ns	ns	-	-	-
Time integrated NDVI (TIN)	-	ns	16.3 _(2,6) **	42.1 _(3,27) ***	102.2 _(1,9) ***	ns	ns	ns	ns	-	-	-
TIN growth	-	ns	6.8 _(2,6) *	26.6 _(3,27) ***	37.6 _(1,9) ***	ns	ns	ns	ns	-	-	-
TIN senescence	-	ns	ns	22.3 _(3,27) ***	161.5 _(1,9) ***	ns	ns	ns	ns	-	-	-

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794 **Table 2: Maize total N uptake and N effect from cover crops (NeffCC) (mean $\pm$ ci, n = 8) for half and norm fertilisation. NeffCC values**
795 **under half fertilization were calculated in relation to the halfN control plots for each tillage system (light grey), and values under norm**
796 **fertilization were calculated in relation to the normN control plots (dark grey). (IT: intensive tillage, NT: no tillage, RT: reduced tillage)**
797 **(control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch).**

Tillage	Cover crop	N uptake (kg N ha ⁻¹)	NeffCC (kg N ha ⁻¹)	N uptake (kg N ha ⁻¹)	NeffCC (kg N ha ⁻¹)
		halfN	halfN	normN	normN
IT	Control	131 $\pm$ 16		171 $\pm$ 17	40 $\pm$ 8
	Oilseed radish (RS)	165 $\pm$ 17	33 $\pm$ 20	191 $\pm$ 18	20 $\pm$ 6
	Subclover (TS)	176 $\pm$ 25	43 $\pm$ 29	215 $\pm$ 23	44 $\pm$ 7
	Hairy vetch (VV)	241 $\pm$ 20	109 $\pm$ 27	262 $\pm$ 13	91 $\pm$ 8
NT	Control	133 $\pm$ 19		176 $\pm$ 27	42 $\pm$ 7
	Oilseed radish (RS)	141 $\pm$ 21	7 $\pm$ 7	184 $\pm$ 33	9 $\pm$ 5
	Subclover (TS)	186 $\pm$ 34	52 $\pm$ 22	212 $\pm$ 30	36 $\pm$ 5
	Hairy vetch (VV)	201 $\pm$ 15	67 $\pm$ 17	222 $\pm$ 37	46 $\pm$ 9
RT	Control	101 $\pm$ 21		139 $\pm$ 24	38 $\pm$ 11
	Oilseed radish (RS)	112 $\pm$ 24	11 $\pm$ 11	148 $\pm$ 13	9 $\pm$ 6
	Subclover (TS)	124 $\pm$ 19	23 $\pm$ 12	134 $\pm$ 12	-5 $\pm$ 8
	Hairy vetch (VV)	176 $\pm$ 19	76 $\pm$ 8	223 $\pm$ 16	84 $\pm$ 10

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Fig. 1 Top Aerial picture of experiment II (10.08.2015) computed from drone imagery (eBee AG, SenseFly) with the software Postflight Terra 3D (Pix4D). Arrangement of main plots (tillage) and the crossed-split-plots (cover crop and fertilization) are drawn to illustrate the experimental design. Bottom NDVI index map (10.08.2015) created with the software PostflightTerra 3D (Pix4D, version 4.0.104), which was used to monitor maize growth.

Fig. 2 Maize growth curves (red) fitted over NDVI measurements for two plots in 2015 and the calculated phenological indexes; maxNDVI, Time Integrated NDVI (TIN, divided in TINGrowth and TINsenescence) and Growth Rate (GRate).

Figure 3: Cover crop biomass and weed biomass at cover crop termination (spring) and weed biomass in the maize crop at flowering. The factor tillage (only applied to maize) is not significant for the cover crop data and fertilization is not significant in maize and are therefore not presented. (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch).

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819 **Figure 4: Maize grain yield for the main factor combinations. The circles and triangles are the individual values for experiment I and II. The dashed line**
820 **shows the mean yield level in the reference treatment with intensive tillage, no cover crop and norm fertilisation (ref). * indicate significant difference**
821 **(<0.05) compared to the ref treatment, ns not significantly different from ref (contrast with adjusted p-value after Benjamini and Hochberg).**
822 **(IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch) (normN: norm**
823 **fertilization, halfN: half fertilization).**

824

825 **Figure 5: Maize growth curves (NDVI over growing season, mean $\pm$ ci, n = 4) with four cover crop treatments (red = control; green = oilseed radish (RS);**
 826 **blue = sub. clover (TS); violet = hairy vetch (VV)) under intensive tillage (IT), no tillage (NT) and reduced tillage (RT) and norm and half fertilization. To**
 827 **ease interpretation, the two dashed lines indicate the maximum NDVI value and the day at which it was reached for the reference treatment intensive**
 828 **tillage, no cover crop and norm fertilization (reference treatment).**

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831 **Figure 6: Nitrogen balance of maize for all treatment combinations calculated as N input (Nfert + Nfix) minus N exported by the grains. Positive values**
832 **indicate that not all added nitrogen was removed at harvest while negative values indicate that more N was removed compared to what was added with**
833 **fertilisation and biological N fixation in legumes. The circles and triangles are the individual values for experiment I and II. * indicate values significantly**
834 **different from 0, ns mean no significant differences (contrast with adjusted p-value after Benjamini and Hochberg) (IT: intensive tillage, NT: no tillage,**
835 **RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch) (normN: norm fertilization, halfN: half fertilization).**