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Original Article

# Growth Analysis of Quinoa (*Chenopodium quinoa* Willd.) in Response to Fertilization and Soil Tillage

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**Abstract**

Growth analysis is an appropriate method for plant response to various environmental and cultural conditions during plant life. A 2-year experiment was conducted to evaluate the effect of soil tillage and fertilization on the growth and growth parameters of quinoa crop and to determine the association between yield and growth characteristics at both the single plant and crop stand level. The experiment was laid out in a split-plot design with two replicates, two main plots [conventional (CT) and minimum tillage (MT)] and four sub-plots [fertilization treatments: untreated, inorganic fertilization of 100 (N1) and 200 kg N $ha^{-1}$ (N2) and sheep manure]. The highest absolute growth rate (AGR) and crop growth rate (CGR) values were recorded between the middle of vegetative growth stage and the beginning of anthesis (50-75 DAS) under conventional tillage coupled with manure (AGR: 0.4577 g $day^{-1}$, CGR: 11.44 g $m^{-2}$ $day^{-1}$) and with N2 treatment (AGR: 0.4521 g $day^{-1}$, CGR: 11.31 g $m^{-2}$ $day^{-1}$). Concerning specific leaf area (SLA), the highest value (150.58 $cm^2$ $g^{-1}$) was found at 75 DAS in N2 treatment. Leaf area index (LAI) were positively affected by soil tillage and fertilization with greatest values found under conventional tillage coupled with N2 treatment (5.110 $m^2$ $m^{-2}$). The highest seed yield was observed in N2 treatment (2488 and 2388 kg $ha^{-1}$ under CT and MT, respectively). As a conclusion, the cultivation under conventional tillage and the increasing levels of applied nitrogen up to 200 kg N $ha^{-1}$ increases crop growth and yield.

***Keywords:*** GDDs; growth analysis; indices; quinoa

## Introduction

Quinoa (*Chenopodium quinoa* Willd., Family: Amaranthaceae) is a pseudocereal crop that has been cultivated in the Andes for several thousand years (Cusack, 1984). Currently, quinoa is emerging as an interesting multipurpose crop for farmers and agro-industries. The seed can be used for both human food and animal feedstock, since it is characterized by high nutritional value including high protein content and a wide range of minerals and vitamins (Nowak *et al.*, 2016). In addition to its good nutritional composition, special attention has recently been given to quinoa as an alternative to cereal crops which contain gluten proteins (Bilalis *et al.*, 2017). The whole quinoa plant has been used as a source to feed livestock, including cattle, pigs and poultry (Kakabouki *et al.*, 2014). Moreover, quinoa is commonly accepted to be a stress-tolerant plant, which is well adapted to different environmental conditions mainly due to its wide genetic variability (Razzaghi *et al.*, 2012; Bilalis *et al.*, 2019). In view of its extraordinary nutritional properties and ability to grow in a wide range of marginal environments, the Food and Agriculture Organization of the United Nations (FAO) has identified quinoa as one of the crops that are destined to offer food security in the 21st century, and declared the year 2013 as the international year of quinoa (FAO, 2012).

Agronomic practices (seed rate, plant density, fertilization, tillage system, sowing time and irrigation) are referred to affect crop environment, which in turn

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influences the growth and finally the yield (Bilalis *et al*., 2012; Razzaghi *et al*., 2014; Roussis *et al*., 2019). Fertilization plays a pivotal role in improving crop productivity through the provision of essential nutrients, and especially nitrogen, that are required by the crop plants to carry on their vegetative growth in pace with reproductive growth. In addition, it has been observed that better crop productivity can only be achieved, when the nutrients are applied at an optimum dose which is required by the crop plants (Kakabouki *et al*., 2018). Tillage constitutes one of the most important operations on crop production system. Tillage methods control weeds, provide a suitable seed bed for crop plants, incorporate crop residues into the soil, make the soil loose, enhance chemical reaction and therefore improves all the physicochemical conditions of soil that affect plant growth and development. Conservation tillage, such as minimum tillage, is an ecological approach to soil surface management and seedbed preparation. It has been practicing worldwide as a means of conserving soil moisture, reducing soil erosion, and improving soil organic C, plant-available water capacity, aggregation, and soil water transmission (Busari *et al*., 2015).

Biomass accumulation is the spatial and temporal integration of all plant processes, and therefore, crop dry matter constitutes the most relevant parameter in the study of crop canopies. A basic knowledge of effect of various factors on the rate and time of the dry matter accumulation and distribution in different parts of the plant is actually helpful in improving the productivity through better cultural and fertilization measures as it clarifies the factors that make a plant more or less productive singly or in population (Gardner *et al*., 1985). Growth analysis is an appropriate method for plant response to different environmental and cultural conditions during plant life (Taiz and Zeiger, 2002). Analysis of crop growth and development can provide insight into differences between various treatment inputs that influence yield (Wilson, 1981).

There was no information about the growth analysis of quinoa crop, especially under Mediterranean semi-arid conditions. Therefore, the aim of current study was to investigate the effect of tillage system and fertilization on the growth and growth parameters of quinoa crop and to determine the association between yield and growth characteristics at both the single plant and crop stand level.

## Materials and Methods

### *Site description and experimental design*

A 3-year field experiment was carried out in the area of Agrinio (Aetolia-Acarnania, Western Greece, Latitude: 38°35′ N, Longitude: 21°25′E, Altitude: 80 m above sea level) during 2012 and 2013. The soil was a clay loam (24.9% clay, 61.2% silt, 13.9% sand) with pH (1:2 $H_2O$) 7.4, EC 0.63 mS $cm^{-1}$, 0.152% total nitrogen, a sufficient supply of phosphorus (P Olsen: 175 mg $kg^{-1}$ soil) and potassium (632 mg $kg^{-1}$ soil) and 1.45% organic matter content. The site was managed according to organic agricultural guidelines (EC 834/2007).

The experiment was set up on an area of 850 $m^2$ according to the split plot design with two main plots (conventional tillage: CT, moldboard plowing at 25 cm, followed by one rotary hoeing at 10-15 cm; minimum tillage: MT, chiseling at 25 cm depth followed by chiseling at 10-15 cm) and four sub-plots [fertilization treatments: control, sheep manure (3000 kg $ha^{-1}$, solid, 11.52% N), inorganic fertilization (fertilizer 26-0-0) with 100 kg N $ha^{-1}$ (N1) and 200 kg N $ha^{-1}$ (N2)], and two replications for each treatment. The main plot and sub-plot sizes were 200 $m^2$ and 50 $m^2$, respectively. Fertilizers were applied as basal fertilization. Quinoa (*Chenopodium quinoa* Willd. cv. Faro) was sown by hand in rows 30 cm apart at a depth of 2-3 cm and approximate density of 250,000 plants $ha^{-1}$. Seed sowing was performed on 5th April 2012 and 10th April 2013. Emergence was on 11th and 15th April in 2012 and 2013, respectively. Overhead sprinkler system was also set up on the field. The field area was irrigated 5 times with a total amount of 250 mm in each growing season. Throughout the experimental period, there was no incidence of pest or disease on quinoa crop. Weeds were controlled by hand-hoeing as and when needed and before canopy closure.

### *Sampling, measurements and methods*

Five plant samples were randomly collected from each sub-plot at 25, 50, 75, 100, 125 and 150 Days After Sowing (DAS). The plants selected were divided into stems, green and yellow leaves, inflorescences and grains. Leaf area was measured using an automatic leaf area meter (Delta-T Devices Ltd, Burwell, Cambridge, UK). Above-ground dry matter was determined after drying for 48 hours at 65 °C. These measurements were used for growth analysis. The growth parameters were calculated using the following equations according to Hunt (1990):

*LAI (Leaf Area Index)* = Lca / P $(m^2\,m^{-2})$ (1)

*LAD (Leaf Area Duration)* = $[(LAI_2 + LAI_1) / 2]\,[t_2 - t_1]$ (days) (2)

*SLW (Specific Leaf Weight)* = Lw / La $(g\,cm^{-2})$ (3)

*LWR (Leaf Weight Ratio)* = Lw / W $(g\,g^{-1})$ (4)

*SLA (Specific Leaf Area)* = La / Lw $(cm^2\,g^{-1})$ (5)

*LAR (Leaf Area Ratio)* = La / W $(cm^2\,g^{-1})$ (6)

*AGR (Absolute Growth Rate)* = $(w_2 - w_1)/(t_2 - t_1)$ $(g\,day^{-1})$ (7)

*ALGR (Absolute Leaf Growth Rate)* = $(Lw_2 - Lw_1)/(t_2 - t_1)$ $(g\,day^{-1})$ (8)

*RGR (Relative Growth Rate)* = $(\ln w_2 - \ln w_1)/(t_2 - t_1)$ $(g\,g^{-1}\,day^{-1})$ (9)

*CGR (Crop Growth Rate)* = $1/P\,(Wc_2 - Wc_1)/(t_2 - t_1)$ $(g\,m^{-2}\,day^{-1})$ (10)

Where:

*La* = total one side area of photosynthetically leaf tissue of a plant ($cm^2$),

*Lca* = total one side area of leaf tissue of canopy covering an area of 1 $m^2$ ($m^2$),

*P* = unit ground surface area ($m^2$),

$t_1$ and $t_2$ = time points of quinoa growth,

*Lw* = dry matter of photosynthetically leaf tissue (g).

*W* = total plant dry matter (g), and

*Wc* = total dry matter of canopy covering an area of 1 $m^2$ (g).

*Meteorological data, thermal time and phenological stages*

Meteorological data concerning mean monthly air temperature and precipitation during the cultivation periods are presented in Fig. 1. Total precipitation in 2012 and 2013 (from April to September) was 233.8 and 240.6 mm, respectively. The mean temperature throughout the growing season was 24.2 °C for 2012 and 23.7 °C for 2013.

During the growing cycle of quinoa, heat accumulation in growing degree days (ADD) from sowing until harvest, summing the growing degree days (GDD) in each time period assessed. Growing Degree Days (GDD) was calculated as:

$$GDD_i = \sum_{i}^{n} \left[\frac{Tmax + Tmin}{2}\right] - T_{base} \qquad (11)$$

where, GDDi is the accumulated growing degree days; Tmin and Tmax are the minimum and maximum air temperatures, respectively. $T_{base}$ also is base temperature of quinoa that is equal to 3 °C (Jacobsen and Bach, 1998).

ADD and the dates of measurements and basic phenological stages of the crop are reported in Table 1. To record the developmental stages, 1 $m^2$ of each sub-plot was observed. The phenological stages were evaluated when at least one plant in each sub-plot pointed out that stage. The phenological stages according to the extended BBCH scale were 10 (Cotyledons fully emerged), 12 (second pair of leaves visible - 1st measurement at 25 DAS), 21 (one side shoot visible - 2nd measurement at 50 DAS), 60 (beginning of anthesis - 3rd measurement at 75 DAS), 70 (fruit set - 4th measurement at 100 DAS), 81 (milky grain - 5th measurement at 125 DAS), 89 (ripe grain - 6th measurement at 150 DAS) and 99 (harvested product) (Sosa-Zuniga *et al.*, 2017).

*Statistical analysis*

The experimental data were subjected to statistical analysis using the SigmaPlot 12 statistical software (Systat Software Inc., San Jose, CA, USA). Data of traits produced by tillage system and fertilization treatments in the two years were analyzed adopting 2 X 2 X 4 factorial design (two years; two tillage systems and four fertilization treatments) laid out in a split-plot design with two replications. The Analysis of Variance (ANOVA) used a mixed model, with years and replications as random effects and tillage system and fertilization as fixed effects. Differences between means were separated using Tukey's test. Correlation analyses were used to describe the relationships between growth parameters and yield components using Pearson's correlation. All comparisons were made at the 5% level of significance ($p \leq 0.05$).

Table 1. Accumulated Degree Days (ADD) of basic phenological stages and measurements (expressed in DAS) obtained during the growing cycle for each year

| Developmental Stage / Measurement | 2012 | | 2013 | |
|---|---|---|---|---|
| | DAS | ADD | DAS | ADD |
| Emergence | 5 | 77.8 | 6 | 79.2 |
| 1st Measurement (Second pair of leaves visible) | 25 | 339.7 | 25 | 419.9 |
| 2nd Measurement (One side shoot visible) | 50 | 762.0 | 50 | 871.4 |
| 3rd Measurement (Beginning of anthesis) | 75 | 1280.0 | 75 | 1395.1 |
| 4th Measurement (Fruit set) | 100 | 1938.6 | 85 | 1962.3 |
| 5th Measurement (Milk grain) | 125 | 2602.9 | 100 | 2604.8 |
| 6th Measurement (Ripe grain) | 150 | 3238.5 | 150 | 3210.7 |
| Harvest | 159 | 3445.8 | 158 | 3389.6 |

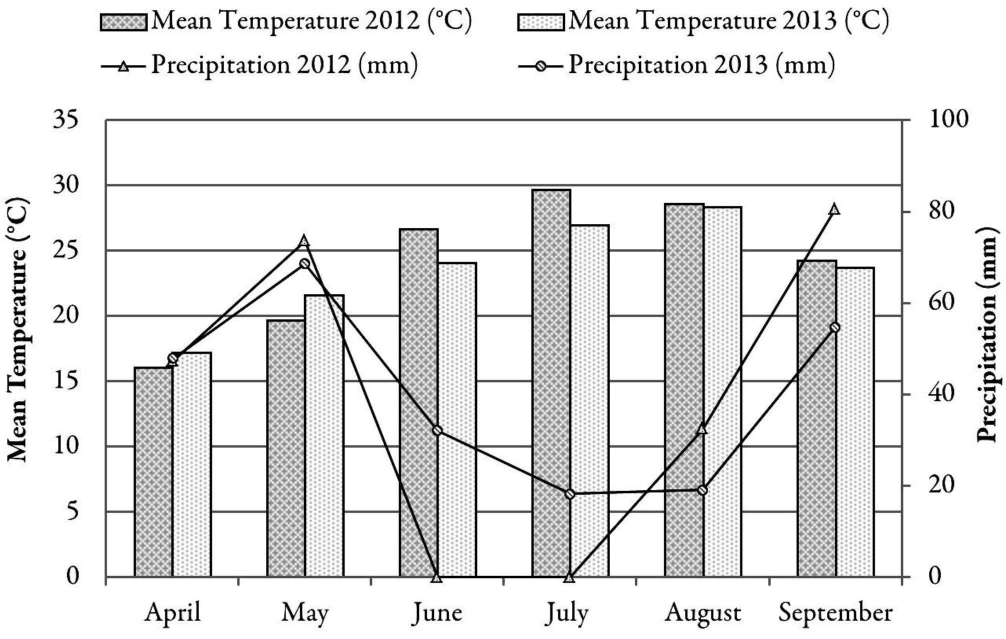


Fig. 1. Meteorological data (mean monthly temperature and precipitation) for experimental site during the growing periods (April-September, 2012 and 2013)

## Results

### *Thermal time and phenology*

The effect of the year associated with accumulated growing degree days (ADD) between phenological stages is shown in Table 1. Although quinoa crop was sown with a difference of five days between the two experimental years (5th and 10th April in the first and second year, respectively), there were no differences in the speed of seedling emergence (seedlings emerged at 5 and 6 days in 2012 and 2013, respectively) and accumulated ADD from sowing to seedling emergence (77.8 and 78.2 in 2012 and 2013, respectively). Significant differences in ADD were found between the stage of second pair of leaves visible and the beginning of anthesis, where the ADD at the beginning of anthesis was 1280.0 and 1395.1 in 2012 and 2013, respectively. However, flowering was not related to ADD, as quinoa was flowered in the same days after sowing (75 DAS) in both years. The differences in accumulated ADD after the seedling emergence and until the anthesis may be explained by the fact that a higher temperature range ($\Delta T$ = 10.6 °C) was observed in the first year than the second one ($\Delta T$ = 6.9 °C) during this period. Finally, quinoa crop was harvested at 159 and 158 DAS in 2012 and 2013, respectively, and the accumulated ADD between years (3445.8 and 3389.6 in the first and second experimental year, respectively) was not differed.

### *Above-ground dry matter, leaf area and leaf dry matter per plant*

The results of the present research study revealed that the dry matter accumulation per plant was significantly affected by different fertilization regimes during seed formation and maturity stages (Table 2). The above-ground dry matter per plant was significantly higher in N2 treatment, and the highest weights observed at 150 DAS with the values being 42.62 and 41.11 g plant$^{-1}$ in 2012 and 2013, respectively.

The effects of the tillage system and fertilization on the dynamics of leaf area growth per plant are presented in Table 3. The maximum values were achieved at the beginning of anthesis (75 DAS). The combined analysis of variance (Table 12) generally revealed that the leaf area was influenced by the tillage system and there was a tendency for leaf area to be higher under conventional tillage than under minimum tillage. A significant difference between the different tillage systems was only observed in the first year (2012) of the experiment, where plants of conventional tillage plots had statistically higher value (1926.51 cm$^2$ plant$^{-1}$), while the lowest value (1833.04 cm$^2$ plant$^{-1}$) was obtained in minimum plots. In regard to fertilization, the highest leaf area (2033.48 cm$^2$ plant$^{-1}$) was found under manure treatment in the first year of the experiment, while, during the second year of this study, the highest value (1970.25 cm$^2$ plant$^{-1}$) was observed in plants treated with the highest rate (200 kg N ha$^{-1}$) of nitrogen fertilizer (N2). However, the differences among N2 and manure treatments were not statistically significant in this 2-year experiment. In response to year, the mean value was higher in 2012 (1879.77 cm$^2$ plant$^{-1}$) than in 2013 (1761.19 cm$^2$ plant$^{-1}$).

As shown in Table 3 and according to the combined analysis of variance (Table 12), the leaf dry matter per plant was only affected by fertilization, and the greatest values observed at 100 DAS. In the first year (2012), there were no significant differences between different fertilization treatments, but during the second year of the experiment, fertilization had a great impact on leaf dry matter with the mean values being 14.63, 14.41 and 13.05 g plant$^{-1}$ for application of N2, manure, and N1 treatment, respectively.

Table 2. Effect of tillage system (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on above-ground dry matter per plant by Tukey's test

| Fertilization | Tillage System | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Above-ground dry matter per plant (g) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| | 2012 | | | | | | | | | | | |
| Control | 5.36 | 5.28 | 14.82 | 14.77 | 25.28 | 23.62 | 32.82 | 32.08 | 35.01 | 33.61 | 36.65 | 35.72 |
| N1 | 5.54 | 5.44 | 15.58 | 15.72 | 27.22 | 26.32 | 34.90 | 33.56 | 37.67 | 36.02 | 40.62 | 38.79 |
| N2 | 5.82 | 5.57 | 16.35 | 16.27 | 28.63 | 27.71 | 36.66 | 34.82 | 40.17 | 39.14 | 43.12 | 42.13 |
| Manure | 5.69 | 5.48 | 16.23 | 16.23 | 29.16 | 28.79 | 36.68 | 36.04 | 39.69 | 38.98 | 42.82 | 41.91 |
| $F_{tillage}$ | 8.76* (Tukey= 0.124) | | 0.01$^{ns}$ | | 7.95* (Tukey= 0.781) | | 0.64$^{ns}$ | | 1.01$^{ns}$ | | 0.72$^{ns}$ | |
| $F_{fertilization}$ | 8.66** (Tukey= 0.169) | | 8.14** (Tukey= 0.893) | | 33.58*** (Tukey= 1.282) | | 1.51$^{ns}$ | | 4.36* (Tukey= 3.199) | | 4.82* (Tukey= 3.599) | |
| $F_{tillage\ X\ fertilization}$ | 0.56$^{ns}$ | | 0.03$^{ns}$ | | 0.61$^{ns}$ | | 0.04$^{ns}$ | | 0.03$^{ns}$ | | 0.03$^{ns}$ | |
| | 2013 | | | | | | | | | | | |
| Control | 5.26 | 5.19 | 14.61 | 14.58 | 23.03 | 21.57 | 32.30 | 31.04 | 33.58 | 32.27 | 34.98 | 33.67 |
| N1 | 5.46 | 5.34 | 15.75 | 15.60 | 24.74 | 24.06 | 34.66 | 31.88 | 36.76 | 33.81 | 38.37 | 35.21 |
| N2 | 5.82 | 5.55 | 17.11 | 16.54 | 27.43 | 27.08 | 36.50 | 36.32 | 38.89 | 38.97 | 41.15 | 41.08 |
| Manure | 5.75 | 5.53 | 16.64 | 16.19 | 26.60 | 25.91 | 36.40 | 36.08 | 38.61 | 38.46 | 40.73 | 40.41 |
| $F_{tillage}$ | 6.42* (Tukey= 0.075) | | 1.12$^{ns}$ | | 2.51$^{ns}$ | | 1.00$^{ns}$ | | 0.83$^{ns}$ | | 1.05$^{ns}$ | |
| $F_{fertilization}$ | 10.46** (Tukey= 0.191) | | 12.22** (Tukey= 0.776) | | 19.03*** (Tukey= 1.489) | | 4.21* (Tukey= 3.157) | | 5.71* (Tukey= 3.321) | | 7.34* (Tukey= 3.359) | |
| $F_{tillage\ X\ fertilization}$ | 0.47$^{ns}$ | | 0.20$^{ns}$ | | 0.22$^{ns}$ | | 0.28$^{ns}$ | | 0.34$^{ns}$ | | 0.35$^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha$ = 0.05). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

Table 3. Effect of tillage system (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on leaf area and leaf dry matter per plant by Tukey's test

| Fertilization | Tillage System | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Leaf area per plant (cm$^2$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| 2012 | | | | | | | | | | | | |
| Control | 98.24 | 96.77 | 719.47 | 717.05 | 1715.01 | 1602.15 | 1719.24 | 1778.10 | 1336.97 | 1283.35 | 683.70 | 666.53 |
| N1 | 102.24 | 99.71 | 765.46 | 762.92 | 1868.01 | 1785.52 | 1703.49 | 1783.19 | 1455.06 | 1375.47 | 766.56 | 723.84 |
| N2 | 109.66 | 104.47 | 828.65 | 813.15 | 2065.69 | 1934.86 | 1881.52 | 1862.89 | 1599.35 | 1541.82 | 838.28 | 812.30 |
| Manure | 106.92 | 102.53 | 818.16 | 809.26 | 2057.32 | 2009.65 | 1902.39 | 1743.84 | 1570.71 | 1529.04 | 827.90 | 803.08 |
| $F_{tillage}$ | $12.18^{**}$ (Tukey= 1.149) | | $0.27^{ns}$ | | $7.09^{*}$ (Tukey= 88.462) | | $0.03^{ns}$ | | $1.60^{ns}$ | | $1.16^{ns}$ | |
| $F_{fertilization}$ | $18.71^{***}$ (Tukey= 3.121) | | $11.60^{***}$ (Tukey= 36.257) | | $24.34^{***}$ (Tukey= 26.546) | | $1.37^{ns}$ | | $7.07^{*}$ (Tukey= 127.171) | | $7.42^{*}$ (Tukey= 69.573) | |
| $F_{tillage\ X\ fertilization}$ | $0.77^{ns}$ | | $0.05^{ns}$ | | $0.27^{ns}$ | | $1.04^{ns}$ | | $0.03^{ns}$ | | $0.04^{ns}$ | |
| 2013 | | | | | | | | | | | | |
| Control | 96.17 | 94.73 | 683.89 | 681.59 | 1578.65 | 1478.44 | 1673.65 | 1730.95 | 1300.99 | 1248.82 | 639.66 | 623.60 |
| N1 | 100.63 | 97.60 | 731.64 | 725.19 | 1715.98 | 1649.81 | 1667.33 | 1735.91 | 1423.48 | 1338.46 | 721.01 | 677.21 |
| N2 | 111.73 | 103.71 | 819.83 | 784.65 | 2021.89 | 1918.63 | 1908.13 | 1842.73 | 1619.07 | 1523.76 | 816.98 | 771.45 |
| Manure | 106.46 | 101.54 | 791.53 | 779.02 | 1900.17 | 1826.02 | 1885.72 | 1722.56 | 1554.82 | 1508.28 | 788.33 | 761.63 |
| $F_{tillage}$ | $7.52^{*}$ (Tukey= 1.751) | | $0.63^{ns}$ | | $3.03^{ns}$ | | $0.21^{ns}$ | | $2.12^{ns}$ | | $1.70^{ns}$ | |
| $F_{fertilization}$ | $11.54^{**}$ (Tukey= 5.974) | | $9.37^{**}$ (Tukey= 47.988) | | $15.63^{**}$ (Tukey= 146.572) | | $2.34^{ns}$ | | $8.18^{**}$ (Tukey= 136.921) | | $8.69^{**}$ (Tukey= 70.924) | |
| $F_{tillage\ X\ fertilization}$ | $0.79^{ns}$ | | $0.17^{ns}$ | | $0.05^{ns}$ | | $0.98^{ns}$ | | $0.06^{ns}$ | | $0.08^{ns}$ | |
| | Leaf dry matter per plant (g) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| 2012 | | | | | | | | | | | | |
| Control | 2.79 | 2.75 | 6.67 | 6.64 | 11.16 | 10.43 | 12.99 | 12.69 | 11.64 | 11.17 | 7.32 | 7.14 |
| N1 | 2.88 | 2.84 | 7.04 | 7.06 | 12.09 | 11.62 | 13.88 | 13.28 | 12.59 | 11.98 | 8.16 | 7.75 |
| N2 | 3.05 | 2.92 | 7.52 | 7.42 | 12.91 | 12.41 | 14.80 | 13.97 | 13.64 | 13.23 | 8.79 | 8.54 |
| Manure | 2.98 | 2.87 | 7.45 | 7.40 | 13.16 | 12.90 | 14.84 | 14.48 | 13.44 | 13.14 | 8.71 | 8.48 |
| $F_{tillage}$ | $11.64^{**}$ (Tukey= 0.021) | | $0.08^{ns}$ | | $9.08^{*}$ (Tukey= 0.431) | | $0.87^{ns}$ | | $1.29^{ns}$ | | $0.92^{ns}$ | |
| $F_{fertilization}$ | $15.25^{**}$ (Tukey= 0.098) | | $10.34^{**}$ (Tukey= 0.302) | | $37.03^{***}$ (Tukey= 0.616) | | $2.15^{ns}$ | | $5.69^{*}$ (Tukey= 1.082) | | $5.98^{*}$ (Tukey= 0.634) | |
| $F_{tillage\ X\ fertilization}$ | $0.78^{ns}$ | | $0.04^{ns}$ | | $0.36^{ns}$ | | $0.05^{ns}$ | | $0.02^{ns}$ | | $0.04^{ns}$ | |
| 2013 | | | | | | | | | | | | |
| Control | 2.87 | 2.83 | 6.97 | 6.95 | 11.34 | 10.62 | 12.64 | 12.15 | 11.05 | 10.62 | 7.11 | 6.84 |
| N1 | 2.99 | 2.92 | 7.55 | 7.43 | 12.26 | 11.85 | 13.63 | 12.47 | 12.16 | 11.13 | 7.84 | 7.16 |
| N2 | 3.25 | 3.09 | 8.38 | 8.03 | 13.93 | 13.58 | 14.81 | 14.44 | 13.33 | 13.04 | 8.71 | 8.47 |
| Manure | 3.19 | 3.05 | 8.08 | 7.83 | 13.41 | 12.94 | 14.50 | 14.32 | 12.94 | 12.82 | 8.43 | 8.31 |
| $F_{tillage}$ | $6.85^{*}$ (Tukey= 0.057) | | $1.47^{ns}$ | | $2.78^{ns}$ | | $1.43^{ns}$ | | $1.30^{ns}$ | | $1.60^{ns}$ | |
| $F_{fertilization}$ | $13.49^{**}$ (Tukey= 0.066) | | $13.44^{**}$ (Tukey= 0.424) | | $17.63^{***}$ (Tukey= 0.865) | | $5.47^{*}$ (Tukey= 1.298) | | $7.04^{*}$ (Tukey= 1.159) | | $8.50^{**}$ (Tukey= 0.515) | |
| $F_{tillage\ X\ fertilization}$ | $0.47^{ns}$ | | $0.24^{ns}$ | | $0.08^{ns}$ | | $0.22^{ns}$ | | $0.24^{ns}$ | | $0.22^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha$ = 0.05). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

*Seed yield*

The combined analysis of variance revealed that the seed yield was only influenced by fertilization (Table 12). Averaged over tillage systems and years, the highest values were found in N2 treatment (2413 kg ha$^{-1}$) followed by manure (2343 kg ha$^{-1}$) and N1 treatment (2304 kg ha$^{-1}$). Concerning the year, the mean value was higher in 2012 (2402 kg ha$^{-1}$) than in 2013 (2165 kg ha$^{-1}$).

*Growth indices of individual plants*

Absolute growth rate (AGR) constitutes the simplest growth index and expresses the rate of change in size per unit time. AGR index was significantly affected by the different tillage system and fertilization regimes (Table 5). The maximum values were reached in the growing period between the middle of vegetative growth stage and the beginning of anthesis (50-75 DAS). Averaged over fertilization treatments and years, the highest value (0.4250 g day$^{-1}$) was recorded under conventional tillage. In response to fertilization, the highest values were found in manure (0.4515 g day$^{-1}$) and N2 treatment (0.4458 g day$^{-1}$). Concerning the year, the mean value was higher in 2012 (0.4537 g day$^{-1}$) than in 2013 (0.3670 g day$^{-1}$).

The absolute growth rate of the leaf weight (ALGR) was characterized by two phases. The first phase was characterized by positive values expressing the leaf growth and the increase of leaf dry matter, while the second phase was characterized by negative values expressing the weight loss due to the leaf withering (Table 5). The maximum values of ALGR were achieved in the timespan between the middle of vegetative growth stage and the beginning of anthesis (50-75 DAS). The mean values of ALGR provided a good evidence of the soil tillage effect. Averaged over fertilization and years, the highest value (0.2030 g $day^{-1}$) was achieved in conventional tillage plots. In response to fertilization, the mean value of ALGR were significantly higher in manure (0.2164 g $day^{-1}$) and N2 treatment (0.2148 g $day^{-1}$).

Relative growth rate (RGR) is an index that expresses growth in terms of the rate of increase in size per unit of size. RGR index was presented an initial rapid increase with the highest values presented between the early and the middle stages of vegetative growth (25-50 DAS), and then this index declined until the grain maturity (Table 6). The combined analysis of variance revealed that RGR was significantly affected by fertilization (Table 12). Averaged over fertilization treatments and years, the mean values of RGR were the greatest in the manure (0.0430 g $g^{-1}$ $day^{-1}$) and N2 treatment (0.0429 g $g^{-1}$ $day^{-1}$), followed by N1 (0.0425 g $g^{-1}$ $day^{-1}$) and control (0.0410 g $g^{-1}$ $day^{-1}$).

Leaf area ratio (LAR) is the ratio between total leaf area and total weight of individual plant. The maximum values of LAR were found at the beginning of anthesis (75 DAS) and then declined gradually until the grain maturity stage (Table 7). LAR was significantly affected by different fertilization regimes, and the highest values (70.98 and 72.25 $cm^2$ $g^{-1}$ in 2012 and 2013, respectively) were recorded in plants fertilized with highest rate (200 kg N $ha^{-1}$) of nitrogen fertilizer (N2) followed by manure (70.19 and 70.93 $cm^2$ $g^{-1}$ in 2012 and 2013, respectively) and N1 treatment (68.23 and 68.95 $cm^2$ $g^{-1}$ in 2012 and 2013, respectively).

Specific leaf area (SLA) constitutes an index that measures relative thinness of leaf and defined as the ratio between total leaf area and total leaf weight of individual plant. SLA index was significantly affected by the fertilization and the maximum values were reached at the beginning of anthesis (75 DAS) (Table 7). The highest values (157.99 and 143.16 $cm^2$ $g^{-1}$ in 2012 and 2013, respectively) were recorded in N2 treatment, while the lowest values were found in control plots (153.67 and 139.24 $cm^2$ $g^{-1}$ in 2012 and 2013, respectively). In response to the year, the mean value was higher in 2012 (155.46 $cm^2$ $g^{-1}$) than in 2013 (140.86 $cm^2$ $g^{-1}$).

Leaf weight ratio (LWR) is an index that measures the plant leafiness on a dry weight basis and defined as the ratio between total leaf weight and total weight of individual plant. The maximum LWR values were observed at the early stage of vegetative growth (25 DAS) and then were gradually decreased until the grain maturity (150 DAS) (Table 8). According to the combined analysis of variance, LWR was only affected by fertilization (Table 12). Averaged over tillage system and years, the mean value was the highest in the N2 treatment (0.540 g $g^{-1}$), followed by manure (0.539 g $g^{-1}$), N1 (0.535g $g^{-1}$), and control (0.532 g $g^{-1}$). Concerning the year, the mean value was higher in 2013 (0.551 g $g^{-1}$) than in 2012 (0.522 g $g^{-1}$).

As with the LWR, specific leaf weight (SLW) is also an index that measures the plant leafiness on a dry basis. It is defined as the ratio between total leaf area and total leaf weight of individual plant. SLW was significantly affected by fertilization and the maximum values were recorded at the early stage of vegetative growth (25 DAS). The mean value of SLW reduced to the N2 treatment, and the mean values in the separate treatments were as follows: control: 0.0292, N1: 0.0290, manure: 0.0289 and N2 treatment: 0.0286 g $cm^{-2}$ (Table 8).

*Growth indices of the crop stand*

Crop growth rate (CGR) indicates the efficiency of the complete crop over a specific land area in the production of biomass. In this research study, the dynamics of CGR were similar to those of AGR due to the fact that AGR constitutes the slope of CGR's curve. The maximum values of CGR were obtained between the middle of the vegetative growth stage and the beginning of anthesis (50-75 DAS). AGR index was significantly affected by the different tillage system and fertilization regimes (Table 12). Averaged over years and fertilization treatments, the highest value (10.63 g $m^{-2}$ $day^{-1}$) was recorded under conventional tillage system (Table 9). Regarding the fertilization treatments, the highest values were found in manure (11.29 g $m^{-2}$ $day^{-1}$) and N2 treatment (11.14 g $m^{-2}$ $day^{-1}$). In response to the year, the mean value was higher in 2012 (11.34 g $m^{-2}$ $day^{-1}$) than in 2013 (9.18 g $m^{-2}$ $day^{-1}$).

Leaf area index (LAI) is defined as the total leaf area of the crop over a unit of the land. The effects of tillage and fertilization on LAI were significant during the cultivation periods and the highest values were achieved at the beginning of anthesis (75 DAS) (Tables 10 and 12). Averaged over years and fertilization treatments, the value of LAI in conventional tillage (4.66 $m^2$ $m^{-2}$) was higher than in minimum tillage plots (4.44 $m^2$ $m^{-2}$). Concerning the effect of fertilization, the maximum values were found in N2 treatment (4.96 $m^2$ $m^{-2}$) and manure (4.87 $m^2$ $m^{-2}$).

Table 4. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N $ha^{-1}$ (N1), inorganic fertilization 200 kg N $ha^{-1}$ (N2) and sheep manure) on seed yield by Tukey's test.

| Fertilization | Tillage System | | | |
|---|---|---|---|---|
| | CT | MT | CT | MT |
| | Seed Yield (kg $ha^{-1}$) | | | |
| | 2012 | | 2013 | |
| Control | 2355 | 2080 | 1960 | 1900 |
| N1 | 2465 | 2306 | 2185 | 2260 |
| N2 | 2595 | 2295 | 2380 | 2380 |
| Manure | 2625 | 2495 | 2067 | 2185 |
| $F_{tillage}$ | $4.56^{ns}$ | | $0.39^{ns}$ | |
| $F_{fertilization}$ | $1.99^{ns}$ | | 12.73** (Tukey= 202.9) | |
| $F_{tillage \times fertilization}$ | $0.17^{ns}$ | | $0.56^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test (α = 0.05). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

In response to the year, the mean value was higher in the first year (4.70 $m^2$ $m^{-2}$) than in the second one (4.39 $m^2$ $m^{-2}$).

Leaf area duration (LAD) is a quantitative measure of green leaf retention over time. The effect of the soil tillage and fertilization treatments on LAD are presented in Table 11.

The maximum values were recorded in the period between flowering stage and the first days of grain formation (75-100 DAS). The highest LAD values, averaged over years and tillage system treatments, were achieved in N2 treatment and manure with the values being 120.59 and 117.56 days.

Table 5. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N $ha^{-1}$ (N1), inorganic fertilization 200 kg N $ha^{-1}$ (N2) and sheep manure) on absolute growth rate (AGR) and absolute leaf growth rate (ALGR) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Absolute Growth Rate (g $day^{-1}$) | | | | | | | | | |
| | 25-50 DAS | | 50-75 DAS | | 75-100 DAS | | 100-125 DAS | | 125-150 DAS | |
| 2012 | | | | | | | | | | |
| Control | 0.3786 | 0.3798 | 0.4184 | 0.3539 | 0.3016 | 0.3386 | 0.0875 | 0.0609 | 0.0655 | 0.0848 |
| N1 | 0.4016 | 0.4112 | 0.4656 | 0.4241 | 0.3072 | 0.2896 | 0.1105 | 0.0982 | 0.1181 | 0.1112 |
| N2 | 0.4212 | 0.4282 | 0.4913 | 0.4574 | 0.3214 | 0.2847 | 0.1404 | 0.1727 | 0.1180 | 0.1195 |
| Manure | 0.4218 | 0.4300 | 0.5168 | 0.5022 | 0.3012 | 0.2902 | 0.1203 | 0.1177 | 0.1252 | 0.1170 |
| $F_{tillage}$ | $0.66^{ns}$ | | $8.83^{*}$ (Tukey= 0.01827) | | $0.02^{ns}$ | | $0.03^{ns}$ | | $0.03^{ns}$ | |
| $F_{fertilization}$ | $7.41^{*}$ (Tukey= 0.02117) | | $16.14^{***}$ (Tukey= 0.04691) | | $0.05^{ns}$ | | $7.44^{*}$ (Tukey= 0.03706) | | $6.63^{*}$ (Tukey= 0.02335) | |
| $F_{tillage\ X\ fertilization}$ | $0.05^{ns}$ | | $0.63^{ns}$ | | $0.10^{ns}$ | | $1.01^{ns}$ | | $0.57^{ns}$ | |
| 2013 | | | | | | | | | | |
| Control | 0.3742 | 0.3757 | 0.3366 | 0.2793 | 0.3710 | 0.3790 | 0.0510 | 0.0491 | 0.0560 | 0.0560 |
| N1 | 0.4115 | 0.4102 | 0.3598 | 0.3386 | 0.3969 | 0.3127 | 0.0839 | 0.0772 | 0.0648 | 0.0561 |
| N2 | 0.4516 | 0.4396 | 0.4130 | 0.4216 | 0.3627 | 0.3697 | 0.0958 | 0.1056 | 0.0904 | 0.0845 |
| Manure | 0.4355 | 0.4268 | 0.3986 | 0.3886 | 0.3919 | 0.4069 | 0.0881 | 0.0951 | 0.0851 | 0.0778 |
| $F_{tillage}$ | $0.31^{ns}$ | | $2.88^{ns}$ | | $0.08^{ns}$ | | $0.32^{ns}$ | | $2.99^{ns}$ | |
| $F_{fertilization}$ | $11.11^{*}$ (Tukey= 0.02407) | | $16.94^{***}$ (Tukey= 0.04061) | | $0.15^{ns}$ | | $37.17^{***}$ (Tukey= 0.01101) | | $23.60^{***}$ (Tukey= 0.00983) | |
| $F_{tillage\ X\ fertilization}$ | $0.12^{ns}$ | | $1.39^{ns}$ | | $0.23^{ns}$ | | $1.13^{ns}$ | | $0.37^{ns}$ | |
| | Absolute Leaf Growth Rate (g $day^{-1}$) | | | | | | | | | |
| | 25-50 DAS | | 50-75 DAS | | 75-100 DAS | | 100-125 DAS | | 125-150 DAS | |
| 2012 | | | | | | | | | | |
| Control | 0.1548 | 0.1556 | 0.1801 | 0.1516 | 0.0729 | 0.0906 | -0.0538 | -0.0607 | -0.1728 | -0.1615 |
| N1 | 0.1663 | 0.1692 | 0.2018 | 0.1823 | 0.0718 | 0.0663 | -0.0516 | -0.0521 | -0.1774 | -0.1690 |
| N2 | 0.1787 | 0.1799 | 0.2155 | 0.1995 | 0.0762 | 0.0627 | -0.0466 | -0.0299 | -0.1941 | -0.1871 |
| Manure | 0.1786 | 0.1810 | 0.2284 | 0.2201 | 0.0671 | 0.0629 | -0.0559 | -0.0534 | -0.1893 | -0.1863 |
| $F_{tillage}$ | $0.19^{ns}$ | | $9.66^{*}$ (Tukey= 0.01673) | | $0.01^{ns}$ | | $0.16^{ns}$ | | $2.13^{ns}$ | |
| $F_{fertilization}$ | $7.96^{**}$ (Tukey= 0.01055) | | $18.26^{***}$ (Tukey= 0.02267) | | $0.14^{ns}$ | | $1.36^{ns}$ | | $4.94^{*}$ (Tukey= 0.01465) | |
| $F_{tillage\ X\ fertilization}$ | $0.01^{ns}$ | | $0.52^{ns}$ | | $0.12^{ns}$ | | $0.48^{ns}$ | | $0.12^{ns}$ | |
| 2013 | | | | | | | | | | |
| Control | 0.1639 | 0.1648 | 0.1749 | 0.1467 | 0.0519 | 0.0610 | -0.0635 | -0.0610 | -0.1576 | -0.1510 |
| N1 | 0.1822 | 0.1808 | 0.1882 | 0.1765 | 0.0553 | 0.0249 | -0.0591 | -0.0538 | -0.1727 | -0.1588 |
| N2 | 0.2054 | 0.1979 | 0.2224 | 0.2219 | 0.0348 | 0.0348 | -0.0590 | -0.0564 | -0.1848 | -0.1828 |
| Manure | 0.1955 | 0.1910 | 0.2131 | 0.2044 | 0.0439 | 0.0551 | -0.0629 | -0.0597 | -0.1806 | -0.1806 |
| $F_{tillage}$ | $0.44^{ns}$ | | $3.24^{ns}$ | | $0.02^{ns}$ | | $2.73^{ns}$ | | $0.82^{ns}$ | |
| $F_{fertilization}$ | $11.83^{**}$ (Tukey= 0.01246) | | $16.07^{**}$ (Tukey= 0.02223) | | $0.23^{ns}$ | | $1.84^{ns}$ | | $4.82^{*}$ (Tukey= 0.01714) | |
| $F_{tillage\ X\ fertilization}$ | $0.15^{ns}$ | | $0.72^{ns}$ | | $0.22^{ns}$ | | $0.09^{ns}$ | | $0.25^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha$ = 0.05). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

Table 6. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on relative growth rate (RGR) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Relative Growth Rate (g g$^{-1}$ day$^{-1}$) | | | | | | | | | |
| | 25-50 DAS | | 50-75 DAS | | 75-100 DAS | | 100-125 DAS | | 125-150 DAS | |
| | 2012 | | | | | | | | | |
| Control | 0.0407 | 0.0412 | 0.0214 | 0.0188 | 0.0102 | 0.0121 | 0.0027 | 0.0019 | 0.0019 | 0.0024 |
| N1 | 0.0424 | 0.0425 | 0.0223 | 0.0207 | 0.0099 | 0.0097 | 0.0031 | 0.0029 | 0.0030 | 0.0029 |
| N2 | 0.0423 | 0.0429 | 0.0225 | 0.0213 | 0.0099 | 0.0092 | 0.0037 | 0.0047 | 0.0028 | 0.0030 |
| Manure | 0.0430 | 0.0434 | 0.0235 | 0.0229 | 0.0092 | 0.0090 | 0.0032 | 0.0032 | 0.0030 | 0.0029 |
| $F_{tillage}$ | $1.70^{ns}$ | | $5.99^{*}$ (Tukey= 0.00072) | | $0.02^{ns}$ | | $0.01^{ns}$ | | $0.65^{ns}$ | |
| $F_{fertilization}$ | $4.45^{*}$ (Tukey= 0.00082) | | $4.63^{*}$ (Tukey= 0.00079) | | $0.39^{ns}$ | | $3.27^{ns}$ | | $5.65^{*}$ (Tukey= 0.00035) | |
| $F_{tillage X fertilization}$ | $0.52^{ns}$ | | $0.54^{ns}$ | | $0.18^{ns}$ | | $0.84^{ns}$ | | $0.12^{ns}$ | |
| | 2013 | | | | | | | | | |
| Control | 0.0409 | 0.0414 | 0.0182 | 0.0157 | 0.0136 | 0.0144 | 0.0026 | 0.0026 | 0.0016 | 0.0018 |
| N1 | 0.0424 | 0.0429 | 0.0181 | 0.0174 | 0.0135 | 0.0111 | 0.0039 | 0.0039 | 0.0017 | 0.0016 |
| N2 | 0.0431 | 0.0437 | 0.0189 | 0.0198 | 0.0114 | 0.0118 | 0.0043 | 0.0047 | 0.0023 | 0.0021 |
| Manure | 0.0425 | 0.0430 | 0.0188 | 0.0187 | 0.0126 | 0.0134 | 0.0039 | 0.0043 | 0.0021 | 0.0020 |
| $F_{tillage}$ | $1.44^{ns}$ | | $2.02^{ns}$ | | $0.01^{ns}$ | | $2.51^{ns}$ | | $0.36^{ns}$ | |
| $F_{fertilization}$ | $4.94^{*}$ (Tukey= 0.00043) | | $6.43^{*}$ (Tukey= 0.00020) | | $0.38^{ns}$ | | $41.32^{***}$ (Tukey= 0.00017) | | $5.62^{*}$ (Tukey= 0.00019) | |
| $F_{tillage X fertilization}$ | $0.01^{ns}$ | | $2.93^{ns}$ | | $0.21^{ns}$ | | $0.86^{ns}$ | | $0.32^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$)

Table 7. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on leaf area ratio (LAR) and specific leaf area (SLA) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Leaf Area Ratio (cm$^2$ g$^{-1}$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| | 2012 | | | | | | | | | | | |
| Control | 18.36 | 18.32 | 48.55 | 48.54 | 67.84 | 67.80 | 52.51 | 55.69 | 38.19 | 38.18 | 18.65 | 18.66 |
| N1 | 18.45 | 18.35 | 49.13 | 48.55 | 68.63 | 67.85 | 48.95 | 53.13 | 38.65 | 38.21 | 18.88 | 18.67 |
| N2 | 18.86 | 18.77 | 50.69 | 49.98 | 72.11 | 69.83 | 51.33 | 53.56 | 39.81 | 39.39 | 19.43 | 19.28 |
| Manure | 18.81 | 18.71 | 50.40 | 49.86 | 70.57 | 69.81 | 51.86 | 48.39 | 39.57 | 39.22 | 19.33 | 19.16 |
| $F_{tillage}$ | $2.67^{ns}$ | | $6.07^{*}$ (Tukey= 0.257) | | $3.18^{ns}$ | | $1.81^{ns}$ | | $3.08^{ns}$ | | $2.87^{ns}$ | |
| $F_{fertilization}$ | $28.73^{***}$ (Tukey= 0.136) | | $23.43^{***}$ (Tukey= 0.665) | | $28.73^{**}$ (Tukey= 1.746) | | $2.31^{ns}$ | | $16.14^{***}$ (Tukey= 0.541) | | $18.29^{***}$ (Tukey= 0.249) | |
| $F_{tillage X fertilization}$ | $0.31^{ns}$ | | $0.71^{ns}$ | | $0.79^{ns}$ | | $2.26^{ns}$ | | $0.36^{ns}$ | | $0.35^{ns}$ | |
| | 2013 | | | | | | | | | | | |
| Control | 18.29 | 18.25 | 46.81 | 46.75 | 68.55 | 68.54 | 51.75 | 56.11 | 38.71 | 38.78 | 18.26 | 18.53 |
| N1 | 18.43 | 18.26 | 46.47 | 46.49 | 69.35 | 68.56 | 48.17 | 54.57 | 38.75 | 39.67 | 18.80 | 19.26 |
| N2 | 19.19 | 18.68 | 47.86 | 47.43 | 73.64 | 70.86 | 52.25 | 50.75 | 41.60 | 39.11 | 19.84 | 18.78 |
| Manure | 18.51 | 18.37 | 47.57 | 48.12 | 71.38 | 70.48 | 51.79 | 47.76 | 40.27 | 39.26 | 19.35 | 18.87 |
| $F_{tillage}$ | $1.90^{ns}$ | | $0.01^{ns}$ | | $2.30^{ns}$ | | $0.73^{ns}$ | | $0.48^{ns}$ | | $0.24^{ns}$ | |
| $F_{fertilization}$ | $3.66^{ns}$ | | $1.96^{ns}$ | | $5.51^{*}$ (Tukey= 2.292) | | $1.25^{ns}$ | | $0.59^{ns}$ | | $0.94^{ns}$ | |
| $F_{tillage X fertilization}$ | $0.43^{ns}$ | | $0.18^{ns}$ | | $0.64^{ns}$ | | $2.54^{ns}$ | | $0.66^{ns}$ | | $0.75^{ns}$ | |
| | Specific Leaf Area (cm$^2$ g$^{-1}$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| | 2012 | | | | | | | | | | | |
| Control | 35.20 | 35.19 | 108.02 | 108.00 | 153.67 | 153.59 | 132.73 | 140.78 | 114.86 | 114.81 | 93.40 | 93.37 |
| N1 | 35.42 | 35.21 | 108.67 | 108.04 | 154.51 | 153.64 | 122.96 | 134.31 | 115.54 | 114.89 | 93.96 | 93.44 |
| N2 | 35.99 | 35.80 | 110.26 | 109.65 | 160.00 | 155.99 | 127.13 | 133.52 | 117.24 | 116.59 | 95.38 | 95.04 |
| Manure | 35.87 | 35.69 | 109.87 | 109.39 | 156.38 | 155.77 | 128.24 | 120.48 | 116.88 | 116.38 | 95.09 | 94.68 |
| $F_{tillage}$ | $3.04^{ns}$ | | $3.43^{ns}$ | | $2.00^{ns}$ | | $2.59^{ns}$ | | $3.14^{ns}$ | | $3.10^{ns}$ | |
| $F_{fertilization}$ | $16.78^{***}$ (Tukey= 0.258) | | $16.50^{***}$ (Tukey= 0.739) | | $4.26^{*}$ (Tukey= 3.049) | | $3.38^{ns}$ | | $15.48^{**}$ (Tukey= 0.809) | | $22.90^{***}$ (Tukey= 0.581) | |
| $F_{tillage X fertilization}$ | $0.34^{ns}$ | | $0.41^{ns}$ | | $0.87^{ns}$ | | $2.26^{ns}$ | | $0.37^{ns}$ | | $0.41^{ns}$ | |
| | 2013 | | | | | | | | | | | |
| Control | 33.54 | 33.43 | 98.19 | 98.07 | 139.24 | 139.13 | 132.30 | 143.43 | 117.61 | 117.84 | 89.87 | 91.13 |
| N1 | 33.60 | 33.46 | 96.90 | 97.53 | 140.00 | 139.24 | 122.39 | 139.49 | 117.12 | 120.55 | 91.95 | 94.78 |
| N2 | 34.45 | 33.65 | 97.79 | 97.73 | 144.98 | 141.35 | 128.89 | 127.62 | 121.46 | 116.89 | 93.84 | 91.11 |
| Manure | 33.33 | 33.24 | 97.98 | 99.53 | 141.69 | 141.14 | 129.96 | 120.39 | 120.17 | 117.75 | 93.56 | 91.76 |
| $F_{tillage}$ | $1.04^{ns}$ | | $0.42^{ns}$ | | $2.02^{ns}$ | | $1.31^{ns}$ | | $0.10^{ns}$ | | $0.02^{ns}$ | |
| $F_{fertilization}$ | $1.49^{ns}$ | | $0.71^{ns}$ | | $4.23^{*}$ (Tukey= 3.049) | | $2.03^{ns}$ | | $0.06^{ns}$ | | $0.41^{ns}$ | |
| $F_{tillage X fertilization}$ | $0.42^{ns}$ | | $0.26^{ns}$ | | $0.83^{ns}$ | | $2.51^{ns}$ | | $0.45^{ns}$ | | $0.47^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$)

Table 8. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on leaf weight ratio (LWR) and specific leaf weight (SLW) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Leaf Weight Ratio (g g$^{-1}$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| | 2012 | | | | | | | | | | | |
| Control | 0.520 | 0.518 | 0.449 | 0.497 | 0.442 | 0.440 | 0.394 | 0.396 | 0.333 | 0.331 | 0.199 | 0.198 |
| N1 | 0.522 | 0.521 | 0.452 | 0.450 | 0.444 | 0.441 | 0.399 | 0.395 | 0.335 | 0.334 | 0.201 | 0.199 |
| N2 | 0.524 | 0.523 | 0.460 | 0.454 | 0.450 | 0.447 | 0.402 | 0.400 | 0.340 | 0.338 | 0.204 | 0.203 |
| Manure | 0.525 | 0.523 | 0.459 | 0.456 | 0.451 | 0.448 | 0.404 | 0.401 | 0.339 | 0.337 | 0.203 | 0.201 |
| $F_{tillage}$ | $0.03^{ns}$ | | $9.38^{*}$ (Tukey= 0.0022) | | $6.21^{*}$ (Tukey= 0.0017) | | $6.25^{*}$ (Tukey= 0.0019) | | $3.01^{ns}$ | | $2.69^{ns}$ | |
| $F_{fertilization}$ | $1.33^{ns}$ | | $31.12^{**}$ (Tukey= 0.0032) | | $24.34^{***}$ (Tukey= 0.0031) | | $24.20^{***}$ (Tukey= 0.0028) | | $16.91^{***}$ (Tukey= 0.0023) | | $14.86^{**}$ (Tukey= 0.0014) | |
| $F_{tillage\ X\ fertilization}$ | $0.01^{ns}$ | | $1.17^{ns}$ | | $0.70^{ns}$ | | $0.71^{ns}$ | | $0.36^{ns}$ | | $0.32^{ns}$ | |
| | 2013 | | | | | | | | | | | |
| Control | 0.546 | 0.545 | 0.476 | 0.475 | 0.493 | 0.490 | 0.392 | 0.391 | 0.329 | 0.329 | 0.203 | 0.200 |
| N1 | 0.549 | 0.547 | 0.480 | 0.477 | 0.495 | 0.492 | 0.393 | 0.390 | 0.331 | 0.332 | 0.204 | 0.206 |
| N2 | 0.557 | 0.555 | 0.489 | 0.485 | 0.508 | 0.501 | 0.405 | 0.398 | 0.343 | 0.335 | 0.212 | 0.207 |
| Manure | 0.555 | 0.553 | 0.484 | 0.483 | 0.504 | 0.499 | 0.398 | 0.396 | 0.335 | 0.334 | 0.208 | 0.205 |
| $F_{tillage}$ | $3.11^{ns}$ | | $3.13^{ns}$ | | $2.57^{ns}$ | | $2.19^{ns}$ | | $1.82^{ns}$ | | $2.01^{ns}$ | |
| $F_{fertilization}$ | $22.78^{***}$ (Tukey= 0.0034) | | $15.58^{**}$ (Tukey= 0.0040) | | $7.51^{*}$ (Tukey= 0.0055) | | $5.89^{*}$ (Tukey= 0.0049) | | $4.29^{*}$ (Tukey= 0.0030) | | $3.64^{ns}$ | |
| $F_{tillage\ X\ fertilization}$ | $0.40^{ns}$ | | $0.45^{ns}$ | | $1.0423^{ns}$ | | $0.70^{ns}$ | | $0.68^{ns}$ | | $0.80^{ns}$ | |
| | Specific Leaf Weight (g cm$^{-2}$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| | 2012 | | | | | | | | | | | |
| Control | 0.0284 | 0.0282 | 0.0094 | 0.0091 | 0.0064 | 0.0065 | 0.0076 | 0.0071 | 0.0087 | 0.0088 | 0.0107 | 0.0108 |
| N1 | 0.0283 | 0.0281 | 0.0092 | 0.0093 | 0.0065 | 0.0064 | 0.0082 | 0.0074 | 0.0086 | 0.0087 | 0.0106 | 0.0108 |
| N2 | 0.0278 | 0.0279 | 0.0090 | 0.0090 | 0.0063 | 0.0064 | 0.0079 | 0.0075 | 0.0086 | 0.0085 | 0.0104 | 0.0105 |
| Manure | 0.0279 | 0.0280 | 0.0090 | 0.0089 | 0.0064 | 0.0063 | 0.0078 | 0.0083 | 0.0085 | 0.0084 | 0.0105 | 0.0106 |
| $F_{tillage}$ | $3.57^{ns}$ | | $1.80^{ns}$ | | $1.60^{ns}$ | | $2.43^{ns}$ | | $3.00^{ns}$ | | $8.02^{*}$ (Tukey= 0.00004) | |
| $F_{fertilization}$ | $17.62^{***}$ (Tukey= 0.00021) | | $15.67^{**}$ (Tukey= 0.00009) | | $4.00^{ns}$ | | $3.55^{ns}$ | | $9.22^{**}$ (Tukey= 0.00005) | | $36.05^{***}$ (Tukey= 0.00007) | |
| $F_{tillage\ X\ fertilization}$ | $0.43^{ns}$ | | $0.73^{ns}$ | | $0.81^{ns}$ | | $2.65^{ns}$ | | $0.33^{ns}$ | | $0.30^{ns}$ | |
| | 2013 | | | | | | | | | | | |
| Control | 0.0300 | 0.0301 | 0.0101 | 0.0102 | 0.0072 | 0.0070 | 0.0076 | 0.0070 | 0.0085 | 0.0085 | 0.0112 | 0.0110 |
| N1 | 0.0298 | 0.0299 | 0.0103 | 0.0103 | 0.0071 | 0.0072 | 0.0082 | 0.0072 | 0.0086 | 0.0083 | 0.0108 | 0.0106 |
| N2 | 0.0291 | 0.0297 | 0.0102 | 0.0102 | 0.0069 | 0.0071 | 0.0078 | 0.0078 | 0.0082 | 0.0086 | 0.0106 | 0.0110 |
| Manure | 0.0297 | 0.0299 | 0.0102 | 0.0100 | 0.0070 | 0.0072 | 0.0077 | 0.0083 | 0.0083 | 0.0085 | 0.0107 | 0.0109 |
| $F_{tillage}$ | $1.09^{ns}$ | | $0.68^{ns}$ | | $2.00^{ns}$ | | $1.18^{ns}$ | | $0.16^{ns}$ | | $0.02^{ns}$ | |
| $F_{fertilization}$ | $1.42^{ns}$ | | $1.04^{ns}$ | | $3.03^{ns}$ | | $1.99^{ns}$ | | $0.05^{ns}$ | | $0.53^{ns}$ | |
| $F_{tillage\ X\ fertilization}$ | $0.31^{ns}$ | | $0.46^{ns}$ | | $0.67^{ns}$ | | $2.77^{ns}$ | | $0.48^{ns}$ | | $0.37^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

Table 9. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on crop growth rate (CGR) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Crop Growth Rate (g m$^{-2}$ day$^{-1}$) | | | | | | | | | |
| | 25-50 DAS | | 50-75 DAS | | 75-100 DAS | | 100-125 DAS | | 125-150 DAS | |
| | 2012 | | | | | | | | | |
| Control | 9.47 | 9.50 | 10.46 | 8.85 | 7.54 | 8.46 | 2.19 | 1.52 | 1.64 | 2.12 |
| N1 | 10.04 | 10.28 | 11.64 | 10.60 | 7.68 | 7.24 | 2.76 | 2.46 | 2.94 | 2.78 |
| N2 | 10.53 | 10.71 | 12.28 | 11.43 | 8.03 | 7.12 | 3.51 | 4.32 | 2.95 | 2.99 |
| Manure | 10.55 | 10.75 | 12.92 | 12.55 | 7.53 | 7.26 | 3.01 | 2.94 | 3.13 | 2.93 |
| $F_{tillage}$ | $0.66^{ns}$ | | $8.84^{**}$ (Tukey= 0.457) | | $0.02^{ns}$ | | $0.03^{ns}$ | | $0.02^{ns}$ | |
| $F_{fertilization}$ | $7.41^{**}$ (Tukey= 0.499) | | $16.15^{***}$ (Tukey= 1.251) | | $0.05^{ns}$ | | $7.45^{*}$ (Tukey= 0.926) | | $6.62^{*}$ (Tukey= 0.483) | |
| $F_{tillage\ X\ fertilization}$ | $0.05^{ns}$ | | $0.63^{ns}$ | | $0.10^{ns}$ | | $1.00^{ns}$ | | $0.56^{ns}$ | |
| | 2013 | | | | | | | | | |
| Control | 9.35 | 9.39 | 8.42 | 6.98 | 9.27 | 9.48 | 1.28 | 1.23 | 1.42 | 1.37 |
| N1 | 10.28 | 10.25 | 9.00 | 8.47 | 9.92 | 7.82 | 2.10 | 1.93 | 1.62 | 1.45 |
| N2 | 11.29 | 10.99 | 10.33 | 10.54 | 9.07 | 9.24 | 2.40 | 2.64 | 2.26 | 2.11 |
| Manure | 10.88 | 10.67 | 9.96 | 9.71 | 9.80 | 10.17 | 2.20 | 2.38 | 2.13 | 1.95 |
| $F_{tillage}$ | $0.31^{ns}$ | | $2.89^{ns}$ | | $0.08^{ns}$ | | $0.31^{ns}$ | | $0.0135^{ns}$ | |
| $F_{fertilization}$ | $11.13^{**}$ (Tukey= 0.602) | | $16.93^{***}$ (Tukey= 1.015) | | $0.14^{ns}$ | | $37.01^{***}$ (Tukey= 0.276) | | $4.1266^{*}$ (Tukey= 0.64269) | |
| $F_{tillage\ X\ fertilization}$ | $0.12^{ns}$ | | $1.38^{ns}$ | | $0.23^{ns}$ | | $1.13^{ns}$ | | $0.8667^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant ($p > 0.05$).

Table 10. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on leaf area index (LAI) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Leaf Area Index (m$^2$ m$^{-2}$) | | | | | | | | | | | |
| | 25 DAS | | 50 DAS | | 75 DAS | | 100 DAS | | 125 DAS | | 150 DAS | |
| **2012** | | | | | | | | | | | | |
| Control | 0.245 | 0.242 | 1.798 | 1.793 | 4.288 | 4.005 | 4.298 | 4.446 | 3.343 | 3.209 | 1.709 | 1.667 |
| N1 | 0.256 | 0.249 | 1.914 | 1.908 | 4.670 | 4.464 | 4.259 | 4.458 | 3.638 | 3.439 | 1.917 | 1.810 |
| N2 | 0.274 | 0.261 | 2.072 | 2.033 | 5.165 | 4.838 | 4.704 | 4.658 | 3.999 | 3.855 | 2.096 | 2.031 |
| Manure | 0.268 | 0.256 | 2.046 | 2.023 | 5.144 | 5.024 | 4.756 | 4.360 | 3.927 | 3.823 | 2.070 | 2.008 |
| $F_{tillage}$ | 12.43$^{**}$ (Tukey= 0.0059) | | 0.27$^{ns}$ | | 7.10$^{*}$ (Tukey= 0.1212) | | 0.03$^{ns}$ | | 1.59$^{ns}$ | | 1.16$^{ns}$ | |
| $F_{fertilization}$ | 18.33$^{*}$ (Tukey= 0.0104) | | 11.62$^{**}$ (Tukey= 0.0905) | | 24.35$^{***}$ (Tukey= 0.3113) | | 1.37$^{ns}$ | | 7.08$^{*}$ (Tukey= 0.3177) | | 7.44$^{*}$ (Tukey= 0.1737) | |
| $F_{tillage\ X\ fertilization}$ | 0.81$^{ns}$ | | 0.05$^{ns}$ | | 0.27$^{ns}$ | | 1.04$^{ns}$ | | 0.03$^{ns}$ | | 0.05$^{ns}$ | |
| **2013** | | | | | | | | | | | | |
| Control | 0.241 | 0.237 | 1.710 | 1.704 | 3.947 | 3.696 | 4.185 | 4.328 | 3.253 | 3.122 | 1.599 | 1.559 |
| N1 | 0.252 | 0.244 | 1.829 | 1.813 | 4.290 | 4.125 | 4.168 | 4.340 | 3.559 | 3.346 | 1.803 | 1.693 |
| N2 | 0.279 | 0.260 | 2.050 | 1.962 | 5.055 | 4.797 | 4.771 | 4.607 | 4.048 | 3.810 | 2.042 | 1.929 |
| Manure | 0.266 | 0.254 | 1.979 | 1.948 | 4.751 | 4.565 | 4.714 | 4.306 | 3.888 | 3.771 | 1.971 | 1.904 |
| $F_{tillage}$ | 7.20$^{**}$ (Tukey= 0.0046) | | 0.62$^{ns}$ | | 3.03$^{ns}$ | | 0.21$^{ns}$ | | 2.12$^{ns}$ | | 1.70$^{ns}$ | |
| $F_{fertilization}$ | 11.49$^{*}$ (Tukey= 0.0147) | | 9.35$^{**}$ (Tukey= 0.1201) | | 15.61$^{**}$ (Tukey= 0.3665) | | 2.34$^{ns}$ | | 8.17$^{**}$ (Tukey= 0.3425) | | 8.70$^{*}$ (Tukey= 0.1773) | |
| $F_{tillage\ X\ fertilization}$ | 0.75$^{ns}$ | | 0.17$^{ns}$ | | 0.04$^{ns}$ | | 0.98$^{ns}$ | | 0.06$^{ns}$ | | 0.07$^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test (α = 0.05). Significance levels: $^{*}$ p < 0.05; $^{**}$ p < 0.01; $^{***}$ p < 0.001; ns, not significant (p > 0.05).

Table 11. Effect of tillage systems (conventional and minimum tillage: CT and MT, respectively) and fertilization (control, inorganic fertilization 100 kg N ha$^{-1}$ (N1), inorganic fertilization 200 kg N ha$^{-1}$ (N2) and sheep manure) on leaf area duration (LAD) by Tukey's test

| Fertilization | Tillage System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CT | MT | CT | MT | CT | MT | CT | MT | CT | MT |
| | Leaf Area Duration (days) | | | | | | | | | |
| | 25-50 DAS | | 50-75 DAS | | 75-100 DAS | | 100-125 DAS | | 125-150 DAS | |
| **2012** | | | | | | | | | | |
| Control | 25.55 | 25.43 | 76.08 | 72.47 | 107.32 | 105.63 | 95.51 | 95.67 | 63.15 | 60.93 |
| N1 | 27.12 | 26.96 | 82.29 | 79.64 | 111.61 | 111.52 | 98.70 | 98.71 | 69.43 | 65.60 |
| N2 | 29.32 | 28.68 | 90.44 | 85.87 | 123.35 | 118.68 | 108.77 | 106.40 | 76.18 | 73.57 |
| Manure | 28.91 | 28.49 | 89.86 | 88.09 | 123.74 | 117.29 | 108.53 | 102.28 | 74.96 | 72.88 |
| $F_{tillage}$ | 0.52$^{ns}$ | | 4.86$^{ns}$ | | 1.83$^{ns}$ | | 0.49$^{ns}$ | | 1.44$^{ns}$ | |
| $F_{fertilization}$ | 12.31$^{**}$(Tukey= 1.218) | | 23.77$^{***}$(Tukey= 4.623) | | 8.85$^{**}$(Tukey= 7.007) | | 3.43$^{ns}$ | | 7.20$^{*}$(Tukey= 6.137) | |
| $F_{tillage\ X\ fertilization}$ | 0.07$^{ns}$ | | 0.18$^{ns}$ | | 0.36$^{ns}$ | | 0.24$^{ns}$ | | 0.03$^{ns}$ | |
| **2013** | | | | | | | | | | |
| Control | 24.38 | 24.26 | 70.70 | 67.50 | 101.63 | 100.29 | 92.96 | 93.12 | 60.64 | 58.51 |
| N1 | 26.01 | 25.71 | 76.49 | 74.22 | 105.73 | 105.80 | 96.59 | 96.07 | 67.02 | 62.99 |
| N2 | 29.11 | 27.76 | 88.80 | 84.48 | 122.81 | 117.54 | 110.23 | 105.20 | 76.13 | 71.73 |
| Manure | 28.06 | 27.52 | 84.12 | 81.41 | 118.31 | 110.89 | 107.52 | 100.96 | 73.22 | 70.93 |
| $F_{tillage}$ | 0.91$^{ns}$ | | 2.29$^{ns}$ | | 1.64$^{ns}$ | | 0.88$^{ns}$ | | 1.97$^{ns}$ | |
| $F_{fertilization}$ | 9.67$^{**}$(Tukey= 1.654) | | 14.24$^{**}$(Tukey= 5.938) | | 10.03$^{**}$(Tukey= 7.989) | | 4.60$^{*}$(Tukey= 8.791) | | 8.37$^{**}$(Tukey= 6.484) | |
| $F_{tillage\ X\ fertilization}$ | 0.20$^{ns}$ | | 0.05$^{ns}$ | | 0.40$^{ns}$ | | 0.27$^{ns}$ | | 0.07$^{ns}$ | |

F-test ratios are from ANOVA. Different letters within a column indicate significant differences according to Tukey's test (α = 0.05). Significance levels: $^{*}$ p < 0.05; $^{**}$ p < 0.01; $^{***}$ p < 0.001; ns, not significant (p > 0.05).

Table 12. Combined analysis of variance (*F values*) for above-ground dry matter, leaf area and leaf dry matter per plant, seed yield and growth indices of quinoa

| Source of Variance | df | Above-ground dry matter per plant (150 DAS) | Leaf area per plant (75 DAS) | Leaf dry matter per plant (100 DAS) | Seed yield | Absolute Growth Rate (50-75 DAS) | Absolute Leaf Growth Rate (50-75 DAS) | Relative Growth Rate (25-50 DAS) |
|---|---|---|---|---|---|---|---|---|
| Year | 1 | 4.98$^{*}$ | 15.32$^{**}$ | 0.46$^{ns}$ | 17.34$^{***}$ | 97.81$^{***}$ | 0.75$^{ns}$ | 4.06$^{ns}$ |
| Tillage | 1 | 1.73$^{ns}$ | 8.77$^{**}$ | 2.19$^{ns}$ | 2.57$^{ns}$ | 11.18$^{**}$ | 11.46$^{**}$ | 2.41$^{ns}$ |
| Fertilization | 3 | 11.70$^{***}$ | 36.08$^{***}$ | 6.74$^{***}$ | 6.63$^{**}$ | 30.96$^{***}$ | 31.85$^{***}$ | 8.46$^{**}$ |
| Year x Tillage | 1 | 0.01$^{ns}$ | 0.02$^{ns}$ | 0.01$^{ns}$ | 4.77$^{*}$ | 1.13$^{ns}$ | 0.42$^{ns}$ | 1.42$^{ns}$ |
| Year x Fertilization | 3 | 0.12$^{ns}$ | 1.03$^{ns}$ | 0.22$^{ns}$ | 1.95$^{ns}$ | 2.05$^{ns}$ | 2.12$^{ns}$ | 1.05$^{ns}$ |
| Tillage x Fertilization | 3 | 0.25$^{ns}$ | 0.19$^{ns}$ | 0.14$^{ns}$ | 0.49$^{ns}$ | 1.69$^{ns}$ | 1.10$^{ns}$ | 0.24$^{ns}$ |
| Year x Tillage x Fertilization | 3 | 0.08$^{ns}$ | 0.04$^{ns}$ | 0.09$^{ns}$ | 0.03$^{ns}$ | 0.24$^{ns}$ | 0.17$^{ns}$ | 0.16$^{ns}$ |

| Source of Variance | df | Leaf Area Ratio (75 DAS) | Specific Leaf Area (75 DAS) | Leaf Weight Ratio (25 DAS) | Specific Leaf Weight (25 DAS) | Crop Growth Rate (50-75 DAS) | Leaf Area Index (75 DAS) | Leaf Area Duration (75-100 DAS) |
|---|---|---|---|---|---|---|---|---|
| Year | 1 | 3.59$^{ns}$ | 102.23$^{***}$ | 219.38$^{***}$ | 176.89$^{***}$ | 93.41$^{***}$ | 15.33$^{**}$ | 6.22$^{*}$ |
| Tillage | 1 | 3.18$^{ns}$ | 3.99$^{ns}$ | 0.94$^{ns}$ | 2.28$^{ns}$ | 12.67$^{**}$ | 8.76$^{**}$ | 3.43$^{ns}$ |
| Fertilization | 3 | 12.67$^{***}$ | 8.49$^{**}$ | 13.42$^{***}$ | 3.49$^{*}$ | 38.21$^{***}$ | 36.07$^{***}$ | 18.57$^{***}$ |
| Year x Tillage | 1 | 0.03$^{ns}$ | 0.02$^{ns}$ | 1.10$^{ns}$ | 0.25$^{ns}$ | 2.08$^{ns}$ | 0.02$^{ns}$ | 0.01$^{ns}$ |
| Year x Fertilization | 3 | 0.09$^{ns}$ | 0.03$^{ns}$ | 3.32$^{ns}$ | 1.64$^{ns}$ | 1.89$^{ns}$ | 1.02$^{ns}$ | 0.46$^{ns}$ |
| Tillage x Fertilization | 3 | 1.37$^{ns}$ | 1.73$^{ns}$ | 0.13$^{ns}$ | 0.43$^{ns}$ | 1.52$^{ns}$ | 0.19$^{ns}$ | 0.76$^{ns}$ |
| Year x Tillage x Fertilization | 3 | 0.02$^{ns}$ | 0.01$^{ns}$ | 0.14$^{ns}$ | 0.21$^{ns}$ | 0.17$^{ns}$ | 0.03$^{ns}$ | 0.02$^{ns}$ |

Significance levels: $^{*}$ p < 0.05; $^{**}$ p < 0.01; $^{***}$ p < 0.001; ns, not significant (p > 0.05).

## Discussion

The results of growth analysis of quinoa indicated the significant relationships between growth rate parameters and seed yield at both the single plant and crop stand level. The indices AGR, ALGR, and CGR presented a positive correlation with seed yield ($r=0.7875$, $p<0.001$; $r=0.6320$, $p<0.001$; and $r=0.7875$, $p=0.002$, respectively). These results are in accordance with previous studies presenting the significant relationship between growth rate parameters and yield in other crops, such as wheat (Sugár *et al.*, 2017), maize (Bullock *et al.*, 1993), oilseed rape (Hunková *et al.*, 2011) and *Nigella sativa* (Roussis *et al.*, 2019). Seed yield was only affected by fertilization and the highest value was found in plants fertilized with the highest rate of inorganic nitrogen fertilizer (200 kg N $ha^{-1}$). Shams (2012) observed that the increase of nitrogen fertilizer rate from 90 to 360 kg N $ha^{-1}$ increased seed yield of quinoa from 518% to 1394% as compared to untreated (0 kg N $ha^{-1}$). Fertilization with inorganic fertilizer gave greater yields as this type of fertilizer contained soluble inorganic nitrogen with quick availability for quinoa crop (Kakabouki *et al.*, 2018).

The growth rate parameters AGR, ALGR and CGR were positively influenced by different fertilization regimes and these results were in line with the increase in the above-ground dry matter and leaf dry matter. Concerning the soil tillage, the above-mentioned growth rate parameters were significantly higher in conventional tillage system because of the higher dry matters that were found in plants cultivated in soil subjected to conventional tillage. The higher dry matters in conventional tillage system might be due to better soil conditions like lower bulk density and better nutrient availability from deeper layer owing to better pulverization of soil than the minimum tillage (Khan *et al.*, 2014).

The highest AGR and CGR during the vegetative and reproductive growth stage were recorded in plots received the highest rate of inorganic nitrogen fertilizer (200 kg N $ha^{-1}$) or manure. Papastylianou *et al.* (2014) demonstrated the positive impact of manure fertilization on dry matter accumulation in quinoa crop. The progressive increases in the dry mass accumulation of plants, probably, were related to a high availability of nutrients and a greater efficiency in absorption and accumulation of nutrients for formation of new tissues (Bullock *et al.*, 1993). In addition, the increase in the growth rate of quinoa may be associated with the increase in the number of leaves and leaf area.

RGR is one of the most ecologically important parameters of growth analysis and represents the plant efficiency to produce tissues from the existing ones (Hunt, 1990). The two peaks of maximum for RGR during vegetative growth phase and minimum during the grain maturity could explain the significant increase and decrease in plant biomass during these periods, respectively. The RGR index decreased with the increase in plant age of quinoa due to the progressive increase of non-assimilator tissues (El-Darier *et al.*, 2002).

LAR, which is defined as SLA times LWR, is the ratio of photosynthesizing to respiring material within the plant (Hunt, 1990). Both SLA and LAR constitute a ratio of leaf area to mass and decrease in value, as plant leaves become thicker with higher concentration of chlorophyll and photosynthetic cells (Craufurd *et al.*, 1999). Concerning SLA, it was only affected by fertilization and the highest values recorded in plants treated with the highest rate of inorganic nitrogen fertilizer (200 kg N $ha^{-1}$) at the beginning of anthesis (75 DAS). Plants with high SLA value are characterized by high nitrogen concentrations, high carbon dioxide rates and nitrogen uptake per unit leaf and root mass, respectively (Amanullah, 2015). Verily, SLA had a positive and significant correlation with biomass nitrogen content at the beginning of anthesis ($r= 0.4494$, $p=0.009$) (Kakabouki, 2016). A negative and very strong correlation was observed between SLA and SLW ($r=-0.9555$, $p<0.001$) due to the fact that SLA parameter increased with the passage of time, while on the other hand SLW index decreased. The increase in the leaf area per plant and reduction in the leaf dry matter per plant increased SLA index, while the opposite holds for SLW (Hunt, 1990).

In the current study, the maximum LAI and LAD values were recorded in in plants treated with the highest rate of inorganic nitrogen fertilizer (200 kg N $ha^{-1}$) at the beginning of anthesis (75 DAS) and throughout the period between flowering stage and the first days of grain formation (75-100 DAS), respectively. This is in accordance with previous studies demonstrated that increase in above-ground dry matter due to the application of higher rates of nitrogen related with higher LAI and LAD values (Bullock *et al.*, 1993; Sugár *et al.*, 2017). Seed yield had a positive and close association with LAI and LAD ($r=0.7479$, $p<0.001$ and $r=0.7183$, $p<0.001$, respectively). Several studies have pointed out the positive and strong correlation between LAI and seed yield (Sugár *et al.*, 2017; Roussis *et al.*, 2019).

## Conclusions

The results of the current study revealed that growth parameters at both the single plant and crop stand level were affected by soil tillage and fertilization. The highest above-ground and leaf dry matter per plant were observed under $N_2$ treatment. In terms of leaf area per plant, there were significant differences among tillage systems and fertilization regimes with the highest values obtained under conventional tillage and $N_2$ fertilization. The highest seed yield was found in $N_2$ plots. Concerning the growth rates, AGR, ALGR and CGR were affected by the different tillage systems and fertilization treatments, with the highest values under conventional tillage coupled with manure and with the highest rate of inorganic nitrogen fertilizer (200 kg N $ha^{-1}$). The highest RGR values were recorded under manure and $N_2$ fertilization treatments. Significantly higher LAR, LWR and SLA were obtained when plants fertilized with the highest rate of inorganic nitrogen fertilizer ($N_2$). SLW was declined with the increase in applied nitrogen rate. LAI was only influenced by fertilization and the highest value observed in $N_2$ plots. The highest LAD values were achieved in $N_2$ treatment and manure. As a conclusion, the cultivation under conventional tillage and the increasing levels of applied nitrogen up to 200 kg N $ha^{-1}$ increases crop growth and yield.

**Conflict of Interest**

The authors declare that there are no conflicts of interest related to this article.

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