Environmental effects on linseed (*Linum usitatissimum* L.) yield and growth of flax at different stand densities

R. Casa a, *, G. Russell b, B. Lo Cascio a, F. Rossini a

a Dipartimento di Produzione Vegetale, Università della Tuscia, Via San Camillo de Lellis, 01100 Viterbo, Italy
b Institute of Ecology and Resource Management, University of Edinburgh, West Mains Road, Edinburgh EH9 3JG, UK

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Abstract

The effect of environmental factors and stand density on linseed (*Linum usitatissimum* L.) yield was investigated by examining yield components and development rates from 4 years of field experiments carried out at Viterbo, Central Italy, in which different seed rates were tested. Spring sowings were carried out using the linseed cultivar 'Mikael'. Growth analysis using the functional approach and modelling using the SUCROS model for potential production parameterized for linseed were used to carry out a more detailed analysis of environmental effects.

Linseed yields varied greatly in response to weather and soil type but showed very little effect of plant density. The crop was able to compensate for reduced stand densities mainly by increasing the number of capsules per plant. All yield components were significantly influenced by weather as represented by the year of sowing. Growth analysis showed that the unit leaf rate had higher values at lower stand densities, suggesting that self-shading at higher densities decreased the efficiency of the foliage. The environmental factors most likely to affect yields were high temperature, due to its effect on development rate, and the consequent shortening of the growing cycle and perhaps water shortage. The foliage duration was more important than the maximum leaf area index. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Growth analysis, Linseed, Stand density, Yield components

1. Introduction

In the search for alternative species to increase diversification of European cropping systems, flax (*Linum usitatissimum* L.) for linseed production has emerged as potentially interesting for a wide range of agro-ecological environments although it certainly cannot be considered a new species, being one of the oldest cultivated plants of mankind. There are several advantages that could come from wider cultivation of this crop in Europe. It is a species with low nitrogen requirements (Hocking et al., 1987), reducing the risk of environmental problems. No specialized farm machinery is needed, as sowing and combine harvesting can be carried out with the same equipment as that used for winter cereals. It is adapted to a wide range of environments, with Canada, Argentina and India being among the world’s largest producers. Seed flax, however, grows best in moderate to cool conditions, particularly during seed filling, and is thus essentially a crop for temperate regions. Experiments carried out in controlled conditions showed that high temperatures during the ripening
phase reduce the number of seeds per capsule and the seed weight and decrease oil yield and quality (Dybing and Zimmerman, 1965). Flax tolerates a wide range of soils, but grows best on well-drained, medium to heavy textured soils, especially silty or clay loams of about pH 6 (Hocking et al., 1987). Although flax is not usually irrigated in Europe, it is susceptible to water stress at the seedling stage, at flowering and during early seed development (Martin et al., 1976). Rainfall or irrigation late in the season can result in a flush of new tillers and leaves, causing uneven ripening (Diepenbrock and Iwersen, 1989). In dry environments, irrigation at flowering and during grain filling considerably increases yields as well as nitrogen-use efficiency (Tiwari et al., 1988; Dutta et al., 1995). European linseed production is insufficient to meet the demand, so the EU is a major importer (Venturi et al., 1994). The largest EU linseed producers are Germany, the UK and France with an average harvested area of 74,000, 64,000 and 47,000 ha, respectively, in the years 1995–1997 (FAO, 1998). Although seed flax has been extensively cultivated in Italy in the past, areas have dramatically dropped in recent years. Unlike the major crops such as wheat, seed flax productivity in Italy has increased less than 20% over the past four decades (FAO, 1998) largely because of the lack of comparable crop-breeding efforts. Genotype-environment interactions have been shown to be high for flax grown in Central Europe (Diepenbrock et al., 1995), and yields vary considerably between seasons, depending on location and weather.

It is therefore important to understand the main environmental causes of yield variation and to determine the most important agronomic factors that influence yield. Sowing time and seed rates are certainly among the key agronomic decisions that have to be taken by farmers and researchers in order to establish how optimal stand density varies with the environment. Experiments carried out to determine optimal sowing rates indicated that satisfactory yields can be obtained in a wide range of stand densities, especially where it is possible to sow flax in autumn as in Southern and Central Italy (D’Antuono and Rossini, 1994). Flax is able to compensate for low stand densities by increasing the number of fertile tillers and of capsules (Diepenbrock and Iwersen, 1989). For spring-sown seed flax, there is less possibility of compensation due to the shortened vegetative phase (D’Antuono and Rossini, 1994). However, there is no general agreement on the optimal seed rate for spring sown flax because of a strong interaction with the environment, including the effect on establishment rate (Natarelli et al., 1995). For example Diepenbrock et al. (1995), in an experiment in 15 locations in Germany and Switzerland, found that yield was unaffected by seed rates varying from 200 to 800 seeds m\(^{-2}\) in the lowest- and in the highest-yielding locations. In the other locations, low and high seed rates yielded less than intermediate rates of 400 and 600 seeds m\(^{-2}\). Growth analysis and modelling provide a way of extending the results from traditional agronomic trials because environmental and management effects can be analysed in more detail, but approaches of this kind seem to be lacking for seed flax agronomic work carried out in recent years. Flax response to temperature has been investigated in the ripening phase in controlled conditions (Dybing and Zimmerman, 1965). However, as the rate of development in flax has been shown to be linearly related to mean air temperature (D’Antuono and Rossini, 1995a), the effect of temperature on the duration of growth might also have important consequences. Nevertheless, studies on the effect of temperature during the vegetative phase in field conditions are lacking. Agronomic studies on the effect of irrigation on linseed have been carried out by Indian authors in a completely different environment and using rather different management practices from those in Europe (Tiwari et al., 1988; Dutta et al., 1995).

Model simulations can be used to investigate whether temperature or rainfall has the more important influence on yield. The SUCROS crop growth model for potential production situations (Spitters et al., 1989) has been recently parameterized for seed flax (Casa et al., 1997). The model was shown to simulate realistically the effect of sowing time and stand density on yields for trials carried out at Viterbo over several years. The objective of the present study was to obtain additional information on physiological responses of
flax to environmental factors in the field and to evaluate how these responses may vary with stand density. Growth analysis and modelling were used as tools to extend the information obtainable from classical agronomic trials.

2. Materials and methods

Four field trials were carried out with the spring seed-flax variety Mikael, at Viterbo, Italy (latitude 42°43'N, longitude 12°07'E, altitude 310 m) in the years 1995–1998. All the trials were carried out in the experimental farm of Viterbo University, in different fields each year, with flax always following wheat. Soils in the area are rather heterogeneous, and the main soil characteristics of the plot used each year are reported in Table 1. Plots were sown in March using sowing rates of 200, 400, 600 and 800 seeds m⁻² in the first 2 years but only of 400 and 800 seeds m⁻² in the other 2 years. The number of treatments was reduced to allow more detailed growth analysis measurements to be carried out. The amounts of seed used were calculated for each target seed rate by taking into account measured germinability, seed weight and increasing by 20% to allow for possible emergence losses. In all years, a randomized complete block design with three replicates was employed. The plot size was 10.5 m² in 1995 and 1996, and 63 m² in 1997 and 1998. The plot size was increased in 1997 and 1998 to allow for periodic harvests for growth analysis. The distance between rows was 15 cm. Phosphorus fertilizer was applied during seedbed preparation using 92 kg P₂O₅ ha⁻¹, and 80 kg N ha⁻¹ was applied as urea, half 15 days after emergence and half at the beginning of stem elongation. Weeding was carried out by hand. The emergence date was established when 50% of the plants emerged, as determined from counts carried out in 6 m lengths of rows per plot each 2 days. The start of flowering was taken to be the day when the first flower appeared in the plots, which were visited at least every 2 days. The components of yield, including stand density, were determined at maturity using samples collected from an area of 0.3 m² per plot in 1995 and 1996 and 0.25 m² in 1997 and 1998. Growth analysis was carried out in 1997 and 1998 by cutting off at ground level all the plants in one 0.25 m² quadrat per plot per harvest. Harvests were carried out weekly in 1997 and fortnightly in 1998. These samples were dried in an oven at 80°C for 48 h and then weighed to determine the above-ground biomass components. Green leaf area was calculated (before drying) by using an electronic area meter (Delta-T Devices, Cambridge, UK) to measure the area of the leaves from a 10 plant sub-sample and scaling up. In 1997 and 1998, the soil moisture content was measured gravimetrically by sampling to a depth of 40 cm in three separate layers (0-10 cm, 10-20 cm, 20-40 cm) with a cheese-type corer (3 cm core diameter). These values were converted to volumetric moisture content using bulk density values, measured in the field at the end of the growing season at four points, for the same depth layers as the moisture samplings, using the excavation method (Blake and Hartge, 1986). Sampling for water content was carried out in each plot weekly in 1997 and twice weekly in 1998. Data were analysed by ANOVA. As no significant difference in soil moisture between the seed rate treatments was found, data from all the points were averaged to describe the seasonal soil moisture trend. Available soil water was computed from measured field capacity and wilting point data. These were obtained in the laboratory, using Richard’s pressure plate appara-

Table 1

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<tr>
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<tbody>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>1.22</td>
<td>1.05</td>
<td>1.17</td>
</tr>
<tr>
<td>Perennial wilting point (m³ m⁻³)</td>
<td>0.11</td>
<td>0.16</td>
<td>0.22</td>
</tr>
<tr>
<td>Field capacity (m³ m⁻³)</td>
<td>0.20</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td>Coarse sand (% w)</td>
<td>31.4</td>
<td>37.3</td>
<td>31.1</td>
</tr>
<tr>
<td>Fine sand (% w)</td>
<td>23.9</td>
<td>30.4</td>
<td>30.7</td>
</tr>
<tr>
<td>Silt (% w)</td>
<td>24.2</td>
<td>14.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Clay (% w)</td>
<td>12.5</td>
<td>17.9</td>
<td>25.6</td>
</tr>
<tr>
<td>Organic matter (% w)</td>
<td>10.9</td>
<td>30.9</td>
<td>17.9</td>
</tr>
<tr>
<td>pH</td>
<td>6.9</td>
<td>6.7</td>
<td>7.3</td>
</tr>
<tr>
<td>Total nitrogen (% w)</td>
<td>0.13</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>Calcium carbonate (% w)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>
The yield components were analysed by ANOVA separately for each year and by a combined ANOVA over the years (Gomez and Gomez, 1983) only for the 400 and 800 m$^{-2}$ treatments, after checking the homogeneity of the years’ error mean squares using Bartlett’s test (Gomez and Gomez, 1983). Trends of above-ground biomass and LAI within each year were analyzed by ANOVA RCB for each growth analysis harvest date in order to test the treatment effects. The crop growth rate (CGR) and unit leaf rate (ULR) were obtained using the functional approach to growth analysis (Hunt, 1982). After conversion to natural logarithms to ensure homosedasticity, functions were fitted to biomass and LAI data, and CGR and ULR were derived analytically. The choice of function was based on F-tests of the increases in sum of squares relative to increases in degrees of freedom moving from more complicated to simpler functions. The functions that were chosen were polynomials of grade 2 for LAI and Richard’s function for above-ground biomass. The latter was used in the form given by Hunt (1982):

$$W = a \left(1 + \exp\left(b - cT\right)\right)^{-1/d},$$

where $W$ is biomass (kg ha$^{-1}$), $T$ is days after emergence and $a$, $b$, $c$ and $d$ are parameters of the function. The results of the curve fitting were tested by breaking up the residual sum of squares into the ‘lack of fit’ and ‘pure error’ components and by making sure by F-tests that the ratio of the respective mean squares was not significant when the significance of the regression was tested (Draper and Smith, 1981).

Estimation of the relative importance of water stress or heat stress on seed yield was carried out using the potential growth version of the SUCROS crop simulation model (Spitters et al., 1989). The parameter values used and other information about the application of SUCROS to linseed have been reported by Casa et al. (1997). The agronomic input data, which were taken from the trials, were the date of emergence, the date when flowering began, and the stand density (Table 2 and 4). Meteorological data were measured at the agro-meteorological station of Viterbo University experimental farm. Since this version of the model takes no account of the soil water balance, the ratio between observed and modelled yield was used to indicate the importance of water shortage independently of any effect of high temperature on the rate of development. Estimates of soil water deficit were only made in 1997 and 1998, so the rainfall between sowing and harvest was used as an index of water availability.

### 3. Results

#### 3.1. Phenology

Plants emerged 12–19 days after sowing (Table 2). Flowering began 41–56 days after emergence and lasted about 1 month, the duration being longest in the earliest emerging crop. The final harvest was carried out once the plants had lost all their green colour. Other phenological data are given in Table 2. In 1997, plants were sown earlier and grew taller in comparison with the other years. In 1996 and 1998, plants reached flowering with a reduced foliage area and height because of a shorter vegetative period. The base

<table>
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<tbody>
<tr>
<td>Sowing</td>
<td>22 March</td>
<td>22 March</td>
<td>6 March</td>
<td>18 March</td>
</tr>
<tr>
<td>Emergence</td>
<td>6 April</td>
<td>3 April</td>
<td>18 March</td>
<td>6 April</td>
</tr>
<tr>
<td>Start of flowering</td>
<td>24 May</td>
<td>18 May</td>
<td>13 May</td>
<td>17 May</td>
</tr>
<tr>
<td>Harvest</td>
<td>21 July</td>
<td>15 July</td>
<td>7 July</td>
<td>15 July</td>
</tr>
<tr>
<td>Emergence to flowering (days)</td>
<td>48</td>
<td>45</td>
<td>56</td>
<td>41</td>
</tr>
<tr>
<td>Total cycle length (days)</td>
<td>121</td>
<td>115</td>
<td>123</td>
<td>119</td>
</tr>
</tbody>
</table>
temperature for this phase was calculated to be 4.8°C using the method of Yang et al. (1995). Using this value, the temperature sum from emergence to beginning of flowering, calculated using the mean daily temperature, averaged 382°Cd (degree days). The maximum LAI, which coincided with full flowering, was reached in 1997 and 1998 at about 400°Cd, which took 16 days fewer from emergence in 1998 (Fig. 1). The higher temperatures and dry conditions during the vegetative development phase in 1998 thus accelerated development and caused a shortening of the growing cycle as compared to cooler years such as 1997.

3.2. Yield components

Seed yields were rather low in 1995 and 1998, and only in 1997 did they exceed 2t ha⁻¹ (Table 3). Yield and plant height were significantly influenced by the year but not by the stand density. Particularly high yields were obtained in 1997 in spite of the difficult emergence period encountered which considerably reduced plant densities (Table 4). The proportion of seeds that developed into mature plants varied considerably from year to year and tended to decrease with seed rate (Table 4). The lowest proportion was 0.39 for the highest seed rate in 1995, and the highest was for the lower seed rate in 1998, when the stand density exceeded the target 400 plants (because of the 20% seed rate increase). The stand density at the highest seed rate ranged from 309 to 711. The soil and weather conditions at or after emergence were the

![Fig 1. Temperature, rainfall and soil moisture trends in the years of the field trials, plotted against days after emergence (DAE). Top: temperature sum from emergence (base temperature = 4.8°C); middle: cumulative rainfall from emergence; bottom: fraction of available soil water (fASW) in the 0–40 cm layer (only for 1997 and 1998) calculated using absolute data for field water capacity in Table 1.](image)

![Fig 2. Relationship between actual stand density and capsules per plant (top) and seeds per plant (bottom) for the four trial years.](image)
Table 3
Results of ANOVA for single years and combined for all years (only for 400 and 800 seeds m$^{-2}$ treatments): yield and plant vegetative development

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height (m)</th>
<th>Seed yield (t ha$^{-1}$)</th>
<th>Harvest index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 seeds m$^{-2}$</td>
<td>0.40 0.63 0.74 0.74</td>
<td>0.74 1.02 0.98 0.98</td>
<td>43.9 27.3 46.1 28.4</td>
</tr>
<tr>
<td>400 seeds m$^{-2}$</td>
<td>0.42 0.64 1.13 1.27</td>
<td>1.13 0.97 1.99 0.98</td>
<td>46.1 26.4 28.4 31.5</td>
</tr>
<tr>
<td>600 seeds m$^{-2}$</td>
<td>0.42 0.58 1.01 0.97</td>
<td>1.01 0.97 1.01 0.97</td>
<td>42.3 26.3 28.4 31.5</td>
</tr>
<tr>
<td>800 seeds m$^{-2}$</td>
<td>0.42 0.59 0.93 1.50</td>
<td>0.93 0.93 1.50 2.10</td>
<td>41.2 22.5 35.3 29.0</td>
</tr>
</tbody>
</table>

CV (%) 4 5 6 7 4 35 81 51 7 3 1 1 4 3

Significance within yearsb ns ns ns ns ns ns ns ns ns ns ns ns

Significance between yearsc *** *** *** ***

a ns, not significant; *, significant at $p \leq 0.05$; **, significant at $p \leq 0.01$; ***, significant at $p \leq 0.001$.
b From ANOVA for single years.
c From combined ANOVA for all years limited to the 400 and 800 seeds m$^{-2}$ treatments.

Table 4
Results of ANOVA for single years and combined for all years (only 400 and 800 seeds m$^{-2}$ treatments): yield components

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Stand density (m$^{-2}$)</th>
<th>Capsules plant$^{-1}$</th>
<th>Seed capsule$^{-1}$</th>
<th>Seed weight (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 seeds m$^{-2}$</td>
<td>141 169 120 16.6 6.8 4.1 6.5 8.7</td>
<td>120 16.6 6.8 4.1 6.5 8.7</td>
<td>169 120 6.8 4.1 6.5 8.7</td>
<td></td>
</tr>
<tr>
<td>400 seeds m$^{-2}$</td>
<td>232 232 216 423 10.8 14.8 16.8 6.5 6.5 4.4 6.9 4.9 7.2 8.3 8.1 6.7</td>
<td>10.8 14.8 16.8 6.5 6.5 4.4 6.9 4.9 7.2 8.3 8.1 6.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 seeds m$^{-2}$</td>
<td>337 399 8.9 8.5 6.4 4.0 7.0 7.4</td>
<td>8.9 8.5 6.4 4.0 7.0 7.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800 seeds m$^{-2}$</td>
<td>308 271 345 622 12.7 12.7 3.8 6.1 3.4 7.0</td>
<td>12.7 12.7 3.8 6.1 3.4 7.0</td>
<td></td>
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</tbody>
</table>

CV (%) 4 5 9 38 16 24 12 34 9 15 16 24 12 34 3 23 4 14 3 4 8 2

Significance within yearsb ns * ns ns ns ** ns ns ns ns ns ns

Significance between yearsc *** *** *** ***

a ns, not significant; *, significant at $p \leq 0.05$; **, significant at $p \leq 0.01$; ***, significant at $p \leq 0.001$.
b From ANOVA for single years.
c From combined ANOVA for all years limited to the 400 and 800 seeds m$^{-2}$ treatments.

due to this deviation from the planned stand density. The years 1995 and 1997 were particularly difficult. In 1995, the air temperature fell below zero for 6 days during the period from sowing to emergence, reaching $-4^\circ$C. The minimum temperature in the 10 days after emergence was lowest in 1995 and 1997 (averaging 2.7 and 4.7°C, respectively) as compared to 1996 and 1998 (averaging 6.2 and 5.8°C). When the temperature dropped below zero, a surface crust was sometimes observed on the soil.

Yield components were more influenced by year and soil than by stand density (Table 4). High plant density significantly decreased the number of capsules per plant ($r = -0.73**$) and seeds per plant ($r = -0.73**$) (Fig. 2). However, the number of capsules per plant was significantly different only in 1995 (Table 4). No correlation was found between stand density and seeds per capsule, which were, however, significantly affected in 1995. Although the higher sowing rate resulted in about 40% fewer capsules per plant than the lower rate on average, the difference was only significant in 1995. From the combined ANOVA over the years, it was found that all traits were significantly influenced by the year (Tables 3 and 4), but that only capsules per plant and harvest index were significantly affected by stand density, while interactions
between year and stand density were never significant (data not shown).

### 3.3 Growth analysis

In an attempt to understand the wide yield variations occurring from year to year, the growth patterns of linseed were examined in detail in 1997 and 1998. These are representative of high and low yielding years, respectively. The fitting of functions to transformed biomass and LAI data gave satisfactory results in general. In fact, the ‘lack of fit’ component of the residual mean square was never significant, and the regressions were always highly significant, even if, in a few cases, standard errors of function parameters were rather high (Table 5). Using temperature sum as the independent variable, instead of DAE, did not reduce the standard errors (results not shown).

The time course of total above-ground biomass and CGR are reported in Fig. 3 for the 1997 and 1998 seasons. The slight decrease in the above-ground biomass after a maximum is reached, more apparent in 1997, can be partly explained by the fact that senescent leaves, which in linseed are detached and lost by the plants, were not harvested.

The total above-ground biomass reached a maximum 80 days after emergence (DAE), i.e. 24 days after the start of flowering, in 1997, whereas in 1998, it reached a plateau at 60 DAE, 19 days after the start of flowering. In 1997, the 800 seeds m$^{-2}$ treatment produced a higher and earlier maximum CGR than the 400 treatment. However, the final biomass was the same in both cases. In 1998, there were no significant differences in above-ground biomass or CGR between the two stand densities. In 1998, for the first 40 DAE, the CGR of both treatments was similar to that of the low stand density one at the same date (not DAE) in the previous year. However, the CGR reached its maximum and then declined. The above-ground biomass totalled about 700 g m$^{-2}$ in 1997 but only about 300 in 1998.

The leaf area index (Fig. 4) in 1997, especially at the lower density, generally followed the typical linseed pattern in which the maximum LAI is reached at flowering and subsequently declines due to senescence (Marshall et al., 1989). However, after the maximum LAI was reached at about 60 DAE, and senescence had started to cause a drop in green leaf biomass and area, rainfalls totalling 68 mm between DAE 76 and 80 resulted in the emergence of new leaves and a temporary delay in the LAI decline. In 1997, a significantly larger maximum LAI was produced by the higher plant density treatment: 2.2 (± 0.23) compared to 1.3 (± 0.22) for the lower plant density.

### Table 5

Parameters of the curves fitted to the time course of natural logarithms and LAI. Richard's function was used for biomass and polynomials of grade 2 for LAI.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>400</th>
<th>800</th>
<th>400</th>
<th>800</th>
<th>400</th>
<th>800</th>
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<tbody>
<tr>
<td>Parameters</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>1997</td>
<td>8.68±0.08</td>
<td>7.72±2.19</td>
<td>0.12±0.03</td>
<td>5.50±1.83</td>
<td>8.70±0.04</td>
<td>8.58±1.63</td>
<td>0.15±0.02</td>
<td>7.36±1.63</td>
</tr>
<tr>
<td>1998</td>
<td>7.91±0.06</td>
<td>7.69±3.76</td>
<td>0.15±0.02</td>
<td>7.00±3.81</td>
<td>7.85±0.10</td>
<td>8.73±6.74</td>
<td>0.18±0.06</td>
<td>9.75±6.41</td>
</tr>
<tr>
<td></td>
<td>-6.422±0.53</td>
<td>0.179±0.023</td>
<td>-0.001±2E-04</td>
<td>0.98±0.02</td>
<td></td>
<td>-6.354±0.48</td>
<td>0.22±0.02</td>
<td>-0.002±2E-04</td>
</tr>
<tr>
<td></td>
<td>-6.117±0.561</td>
<td>0.23±0.02</td>
<td>-0.003±2E-04</td>
<td></td>
<td></td>
<td>-5.831±0.912</td>
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</tr>
<tr>
<td>1997</td>
<td>39</td>
<td>39</td>
<td>21</td>
<td>21</td>
<td>27</td>
<td>27</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>1998</td>
<td>0.94±0.02</td>
<td>0.95±0.05</td>
<td>0.91±0.04</td>
<td>0.90±0.02</td>
<td>0.22±0.01</td>
<td>0.77±0.02</td>
<td></td>
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<tr>
<td>Significance</td>
<td>***</td>
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</table>

*For parameters, see Richard’s function under ‘Materials and methods’.

*ns, not significant; *, significant at p ≤ 0.05; **, significant at p ≤ 0.01; ***, significant at p ≤ 0.001.
there were no significant differences between the
two treatments, and the maxima were low
(1.2 ±0.5) compared with the previous year. This
reduction in LAI in 1998, as compared to 1997, is
even more striking when actual stand densities of
the two years are considered (Table 4). The area
of leaf per plant in 1998 was about one third of
the amount in 1997. ULR had a similar trend in
both years and was considerably higher in the
lower density treatment.

3.4. Modelling the weather effects

In 1998, not only was the weather during the
growing season hotter than in 1997, but cumulative
rainfall was also considerably less (Fig. 1). In
1998, rainfall was no less than in 1997 for the first
35 DAE. However, this period was followed by
32 days without rain, so a large water deficit
developed. In fact, there was virtually no water
available for plant uptake in the upper 0.40 m of
soil from 40 to 65 DAE (Fig. 1). Flax is reported
to be shallow rooting (Hamdi et al., 1973) so the
stress imposed must have been large, although,
since the plants survived, water must have been
taken up from deeper in the soil. Gupta and
Agrawal (1977) showed that seed flax can take up
soil water from below 1.00 m. In 1997, there was
plenty of available water until well after full
flowering.

The SUCROS model was run for the 4 years of
trials (Fig. 5). In terms of rainfall, 1996 was dry,
1995 and 1998 was intermediate and 1997 was wet.
In contrast to the results of Casa et al. (1997), the
modelled yields were overestimated at high stand
densities, although they were close to the observed
yields when the stand density was lower. Indeed,
there was a significant negative correlation (r =
−0.70**) between the ratio of observed to mod-
elled yield and stand density. The ratio for the
lowest stand density (141 m−2) was 0.93, whereas
the ratio for the highest (711 m−2) was 0.72. The
deviations from the regression line were not sig-
ificantly correlated with rainfall.
below 0°C shortly after emergence, poor seedbed conditions, including those caused by frost, might also have contributed, as seed flax is very sensitive to this factor (D’Antuono and Rossini, 1995b; Diepenbrock et al., 1995). These observations confirm that in Central Italy, the risk of frost in the early phases of crop development has to be taken into account for spring sowings.

Seed yields were not affected by stand density in the range tested, confirming the report of Albrechtsen and Dybing (1973), who found no significant yield differences for flax stands ranging from 100 to 700 plants m$^{-2}$. In fact, the increase in the number of capsules per plant at lower stand densities confirms, as has already been reported for other environments (Dillman and Brinsmade, 1938; Albrechtsen and Dybing, 1973; Diepenbrock and Porksen, 1992; Natarelli et al., 1995), that low numbers of flax plants are balanced by increased numbers of capsules per plant due to basal or inflorescence branching. The increase in capsules per plant was sufficient to eliminate significant

4. Discussion

The observed stand density varied greatly between years. Although low rates of emergence were associated with air temperatures dropping

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**Fig. 4.** Trends of leaf area index (LAI) and unit leaf rate (ULR) for 1997 and 1998 plotted against days after emergence (DAE).

**Fig. 5.** Ratio between observed and modelled yields for the years 1995 (●), 1996 (□), 1997 (○) and 1998 (○) plotted against stand density. Simulations were carried out with the model MUCROS as described in the text.
effects of stand density on the number of capsules per unit land area.

Although the harvest index was greater for the lower stand density than for the higher, in agreement with the findings of Diepenbrock and Porksen (1992), higher stand densities did not cause any increase in plant height (Dillman and Brinsmade, 1938; Albrechtsen and Dybing, 1973). The positive correlation between plant height and yield, through the effect on both seed weight and capsules per unit surface, shows the importance of adequate vegetative growth.

Growth analysis data showed, however, that even when the maximum LAI is less than 1.5, as in the lower density in 1997, seed yields of almost 2 t ha\(^{-1}\) can be obtained. ULR was higher for the lower plant density treatment, so the higher efficiency of the photosynthetic organs compensated for the lower leaf area. This suggests that there was significant self-shading at the higher stand density. Although the CGR does not include root biomass, the ULR in the early part of the growing cycle was not considered to have been underestimated by more than 30% with the error becoming progressively smaller as flowering was approached. The values of ULR were similar to those observed in Canadian trials carried out by Marshall et al. (1989), although they reported a much higher biomass (1500 g m\(^{-2}\)) and CGR (50 g m\(^{-2}\) d\(^{-1}\)). The value for CGR should be treated with caution, however, since it is significantly larger than the highest short-term rate for C3 plants tabulated by Monteith (1978). Marshall et al. (1989) also found that a reduction in maximum LAI from 6.0 (wet season) to less than 2.0 (dry season) resulted in a yield reduction of less than 10%, suggesting that the optimum LAI is near 2.0. In our trials, ULR did not differ much between 1997 and 1998, although the maximum ULR, coinciding with the maximum LAI, was reached earlier in 1998. This suggests that the main effect of heat and water stress was on the LAI and not the ULR. In other reports, water and temperature stress have been shown to reduce ULR in linseed (Tiver and Williams, 1943; Marshall et al., 1989) by increasing respiratory losses.

The SUCROS model was shown to predict the effect of stand density poorly. Contrary to expectations, there was no clear effect of rainfall on flax yield once the effect of stand density had been removed. The results of the simulations are consistent with the hypothesis that temperature has a large impact on yield through its effect on rate of development and thus on the duration of growth. The lower temperatures in 1997 slowed down the rate of development of the flax and extended the growing period compared with the other 3 years.

However, the yields obtained suggested that water shortage did indeed reduce seed yields, even though it occurred towards the end of the growing cycle when its effect would have been reduced by mobilization of stem reserves and possibly by a greater water use efficiency of photosynthesis for stems and capsules than for leaves.

Another hypothesis is that the model underestimates potential yield and that yield was reduced by drought in all years. Increasing stand density would hasten the rate of depletion of available water and hence reduce the ratio of observed to modelled yields. The ratio should approach a constant value because the relationship between canopy transpiration and stand density approaches an asymptote. This hypothesis is also consistent with Fig. 5, although there are insufficient data to provide an unequivocal answer.

The farmer has to choose an appropriate seed rate and date of sowing. Although stand density did not have an important influence on yield in the present work, the variable establishment rates suggest that care must be taken when recommending seed rates in case the resultant stand density falls below the threshold where compensation is complete. Increasing seed rates to cover all eventualities is not an economically viable option because of the cost of the seed. Phenological simulation models can be useful aids in planning sowing dates for seed flax to reduce the risks (D’Antuono and Rossini, 1995b) and it would be helpful to extend them to take account of stand density and establishment rate.

5. Conclusion

Linseed yields, in one trial per year carried out over 4 years at Viterbo, Central Italy, varied
greatly in response to weather but showed very little effect of seeding rate. The vulnerability of linseed plants in the establishment phase made it difficult to achieve the planned stand densities. The seed yields obtained in some years were rather low compared to those typically obtained in Central Europe (Diepenbrock et al., 1995) or even in Northern Italy (Natarelli et al., 1995). The environmental factors most likely to be responsible for these yield reductions were high temperature, which caused significant yield losses due to its effect on hastening development rate, and the consequent shortening of the growing cycle and possibly water shortage. From our data, it seems that in Central Italy, the duration of growth is more important than the amount of foliage produced in determining yield, although water deficits may also reduce crop growth rate in some years. The possibility of extending the length of the growing period through earlier sowings seems, however, limited by the difficulties caused by low temperatures in the emergence phase.

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