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The effect of defoliation on the yield of leek (*Allium porrum* L.)

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Abstract

The foliar area loss is a typical damage in crops caused by fungus, insects or hailstorm. A lot of studies have been carried out to describe the effect of defoliation in the main herbaceous and woody crops. The results of two trials carried out in Valle Medio of the Ebro (Spain) are described in this study to determine the effects of different levels of defoliation in several phenological stages in leek crop. Four levels of defoliation were applied: control, slight, moderate and heavy, in six different phenological stages. Defoliations were carried out by means of a jet of water under pressure. According to the results observed, a close relationship between the yield loss with the percentage of defoliation and the crop stage was found. The most critical stage was at the beginning of the stem thickening in which there are maximum losses of 41% with 100% of defoliation. These experimental results were used to obtain regression equations in which the percentage of yield reduction is calculated in relation with the phenological stage and the percentage of defoliation. These equations can be used to improve simulation patterns of the leek growth in case of foliar damages caused by fungus, insect attacks or hailstorm.

Additional key words: foliar damage, hail, simulation, yield loss.

Resumen

Efecto de la defoliación en el cultivo de puerro (*Allium porrum* L.)

La pérdida de área foliar es un daño típico en los cultivos causado por ataques de hongos e insectos o por granizo. Se han realizado numerosos estudios para describir los efectos de la defoliación en los principales cultivos herbáceos y leñosos. En este trabajo se describen los resultados obtenidos en dos ensayos, llevados a cabo en el Valle Medio del Ebro (España), para determinar el efecto en el cultivo de puerro de diferentes niveles de defoliación aplicados en varios estados fenológicos. Se aplicaron cuatro niveles de defoliación: control, leve, medio y alto en seis estados fenológicos diferentes. La defoliación se llevó a cabo con una maquina de agua a presión. Se observó una estrecha relación entre la pérdida de cosecha, el porcentaje de defoliación y el estado fenológico en que se aplicó. El estado más crítico fue al inicio del engrosamiento del tallo en el cual se alcanzaron las mayores pérdidas, de un 41% para un 100% de defoliación. Estos resultados experimentales se utilizaron para obtener ecuaciones de regresión en las que se calculó el porcentaje de pérdida de cosecha en relación con el estado fenológico y el porcentaje de defoliación aplicado. Estas ecuaciones pueden ser utilizadas para mejorar los patrones de simulación de crecimiento del puerro en caso de daños foliares provocados por ataques de hongos o insectos o por granizo.

Palabras clave adicionales: daños foliares, granizo, pérdida de cosecha, simulación.

Introduction

Morphological and physiological responses of plants to stress determine the effects on the final production (Prins and Verkaar, 1992). Simulation models of crop development and growth should take into account these processes in order to simulate correctly the damage suffered and the impact on the yield.

The foliar area loss is a typical damage in crops caused by fungus, insect attacks or hailstorm and several studies have been done to describe defoliation effects on the main herbaceous and woody crops such as *Vitis*

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vinifera, cotton, onion or garlic (Candolfivasconcelos and Koblet, 1990; Muro *et al.*, 1998b, 2000; Longer and Oosterhuis, 1999).

Three different types of responses to plant defoliation have been described (McNaughton, 1983): (1) detrimental effect, which consists of a decrease of growth rate and fitness of attacked plants; (2) no effect, when attacked plants show similar growth rates and fitness to control plants unless a certain damage threshold is reached above which a negative effect occurs; (3) beneficial effect, when, after moderate level of damage, a recovery in plant growth and fitness is observed (Prins *et al.*, 1989). On the other hand, Schneiter *et al.* (1987) and Schneiter and Johnson (1994) pointed out that (a) defoliation affects yield and (b) its occurrence in different developmental stages results in significant differences in final yield.

During most part of life cycle, the leek's bulb is buried, so the factors that cause defoliations rarely produce direct damages on this part of the plant. But they produce indirect damages, because, leaf losses have an impact on yield reduction. These indirect damage assessments present serious problems in some of the cultivated species, covered by agricultural insurances. There are few experimental data for many crops with lesser economical importance, such as leek.

The main objective in this study is to quantify the yield loss caused by different defoliation levels done in several phenological stages of leek and to construct relationships curves based in these results. These curves can be useful for modelling the yield loss due to defoliation caused by biotic and abiotic agents.

Material and methods

Study area and crop

Two experimental trials were carried out on two sites (San Adrián and Calahorra) located in the Valle Medio of the Ebro (Spain). The distance between them was 4 km. The climate was Temperate Mediterranean. The soil of sites was typical of irrigated land on the area, and was characterized as *Xeric torrifluvent.* They are deep calcareous soils with a pH of 7.5-8.0, and a silty-clay-loam (San Adrián trial) or clay-loam texture (Calahorra trial).

The leek cultivar used was Atal (Clause Tezier) which is commonly used in Spain in summer-autumn crops. The crops were planted on the 14th and the15th of July in 2002. Plants had at least 5 mm of caliber. The distance was 1.0 m between rows, and 0.07 m between plants within the row. The cultural practices were the ones that are commonly used in this area (Macua *et al.*, 1993). Furrow irrigation was used. Before making the furrows, 60 UF ha^{-1} of N, 150 UF ha^{-1} of P and 200 UF ha^{-1} of potash were applied and 150 UF ha^{-1} of N at plantation. A pendilmehalin herbicide was applied at plantation and two preventive treatments were made against aphids and rust.

Experimental design

Trial designs were a randomly split-plot with four replications. In the main plot defoliation treatments were applied at six phenological stages, and the sub-plots (four) were made up of 5 lines of plants 2 m long. Each of the four defoliation levels (control, slight, medium and hard) was applied in the sub-plots.

Methodology

The method of traumatic defoliation by using pumped water was applied in the trials to simulate hailstorm effects. Muro *et al.* (1998b), proved that, on equal eliminated areas, they could obtain higher yield loss with the pumped water method than with scissors. Pumped water method combines the mechanic effect produced by hailstone and the humidity effect, so it is more similar to hailstorm than any other method such as scissors.

Defoliation was carried out in six phenological stages (see Table 1) on the same dates in both trials. The defoliations were made by applying pumped water with a

Table 1. Date, number of leaves, and phenological stage (BBCH Scale, Feller *et al.,* 1995) at the times of defoliation in the San Adrián and Calahorra trials

Time of defoliation	Date	Number of true leaves	BBCH stage
1	28th July	5	105
2	11th August	10	110
3	27th August	15	115, 403
4	10th September	16	116, 405
5	25th September	17	117, 405
6	10th October	> 17	117, 407
Harvest	15th-16th December		409

swirl nozzle. The path traced by nozzle produces a strong burst of water that damages the aerial portion of plants. A water pressure washer machine, Kärcher model 1750 G, made up of a compressor, a water tank, and rotating nozzle was used. It applies a flow rate of 500 L h^{-1}, working with a 10 MPa pressure and 3.7 kW power.

The experimental defoliation levels correspond to: control (C- without defoliation), slight defoliation (S-two pass with the defoliation machine), moderate defoliation (M-three pass) and heavy defoliation (H-four pass). Every pass took around 10 s when plants were small and around 30 s when plants were reaching their maximum hight, to get close to 33%, 66% or 99% damage. The nozzle was positioned vertically about 10 cm above the plants and two, three or four turns with machine were carried out to produce damage from lowest to highest.

The leaf area losses in each level of defoliation (C, S, M, H) were measured on four groups of 5 plants located outside the trial plot at each phenological stage. Once the defoliations were done, 5 plants corresponding to each damage level were taken and leaf blades where the colour changed from green to white were cut out and weighed. Moreover, surface of leaf blades of one plant of each defoliation level were measured by image analyser (DIAS from DeltaT) and the ratio fresh weight/surface area was calculated. Starting from the weight of the leaves of the 5 plants and the ratio, the loss of leaf area was determined. By reference to total surfaces of the control plants (0% defoliation) the defoliation percentage of S, M and H plants were calculated. The defoliation levels in each phenological stage and trial are shown in Table 2.

The three central plant rows of each elementary plot were harvested in December, when the stems of the control plants were fully developed. To obtain the marketable yield, roots were removed, and the stems were cut 5 cm above the separation point of the leaf blades at the end of the stem. According to the Spanish quality standard (*Norma de Calidad Española*; MAPA, 1986), the stems with a diameter lower than 10 mm were classified as unmarketable yield and were not weighed. Thus, marketable yield for each sub-plot was obtained.

Equations on the loss of yield

Two-way ANOVA (defoliation level and phenological stage at the time of defoliation) and Student-Newman-Keuls (SNK) test were performed for marketable yield in each trial.

For each subplot, the percentage yield loss was calculated with respect to the control sub-plot (the percentage by which the marketable yield of a defoliated subplot appears diminished in comparison with the marketable yield of a non-defoliated (control) sub-plot). For each defoliation level the following expression was used for each trial and phenological stage.

$$\%\ \text{yield loss} = \frac{\text{Control yield} - \text{Subplot yield}}{\text{Control yield}} \times 100$$

Those values and the percentage defoliation values (16 pairs of values for each phenological stage) were used to plot linear and quadratic regression lines. Quadratic regression was used because the best fit was obtained in most of the cases. Quadratic regression lines were made using $y = ax^2 + bx$ equations where y was the yield loss percentage and x was the defoliation percentage. Regression was used without constant term ($c = 0$), since yield loss should be 0 for a 0% defoliation.

Table 2. The percentage of defoliation (slight, moderate and heavy) applied at different phenological stages (Feller *et al.,* 1995) of leek in the San Adrián and Calahorra trials. Data are the average of 5 replications

Trial	Defoliation	BBCH phenological stage					
		105	110	115/405	116/405	117/405	117/407
San Adrián	Slight	56.7 ± 3.06	32.0 ± 10.06	35.0 ± 15.42	26.3 ± 9.14	35.4 ± 15.05	29.9 ± 11.31
	Moderate	61.7 ± 11.41	79.9 ± 11.69	73.5 ± 13.43	64.0 ± 10.87	64.7 ± 7.89	59.8 ± 3.09
	Heavy	90.5 ± 2.92	94.8 ± 6.41	97.3 ± 8.40	96.0 ± 5.25	99.3 ± 6.72	97.8 ± 4.25
Calahorra	Slight	37.5 ± 12.11	36.3 ± 6.93	43.5 ± 11.37	45.0 ± 8.92	33.6 ± 4.95	35.3 ± 14.93
	Moderate	65.0 ± 10.93	69.6 ± 19.55	70.5 ± 12.84	70.8 ± 19.72	62.2 ± 5.45	60.0 ± 13.61
	Heavy	88.5 ± 1.10	96.9 ± 1.02	96.4 ± 2.72	99.1 ± 1.36	99.5 ± 2.16	99.7 ± 1.16

Results

Effect of defoliations on production

Yield values are shown in Table 3. In both trials the marketable yield of the control plot were significantly different ($P < 0.05$) from the defoliated plots, and at the same time the productions of these defoliations differed significantly from each other. The yield loss was higher according to the degree of defoliation. It was 20% and 15.6% when slight defoliation was applied, 28.6% and 27.9% in case of moderate defoliation and 35.3% and 32.5% for high defoliation respectively in San Adrian and Calahorra trials.

On the other hand the most sensitive phenological stages were not the same in both trials. The most sensitive in Calahorra trial was the stage 3 (115 on the BBCH scale), and its yield was significantly lower than yield of 1, 2 and 6 phenological stages (105, 110 and 117/407 on BBCH scale). In San Adrian trial the stage 4 (116 on the BBCH scale) was the most sensitive and its yield was significantly lower than 1, 2 and 5 phenological stages (105, 110 and 117/405 on BBCH scale).

Analysing the combination of both trials it can be observed that the highest yield loss was with heavy defoliations in phenological stage 3, in both experimental trials. It is important to point out that the yield reduction was calculated on the basis of the reduction in weight of the stems and not on the number of stems per plot, since plant death brought about by defoliation did not produce any significant differences between plots (data not shown).

ANOVA for Calahorra trial showed a significant interaction between phonological stage and defoliation. This is caused by the different responses to defoliation level regarding the phenological stage, that is, the damage caused by the highest defoliation in the critical phenological stage is proportionally much higher than the one caused by the same level of defoliation in other phenological stages.

Yield reduction equations

The value of the coefficients a, b and r^2 and significance of the quadratic equations are shown in Table 4. The square of the correlation coefficients (r^2) were

Table 3. Marketable production ($Mg\ ha^{-1}$) of leek stems subjected to four levels of defoliation (control, slight, moderate and heavy) and six phonological stages. Values are means ± standard deviation of four repetitions

Stage	Defoliation level				
	Control	**Slight**	**Moderate**	**Heavy**	**Mean of defoliated plots**[1]
San Adrián					
1	41.91 ± 2.37	33.79 ± 3.22	33.08 ± 1.84	29.84 ± 3.76	32.24 ± 5.27^{a}
2	44.15 ± 3.10	35.75 ± 1.97	28.63 ± 4.47	26.36 ± 4.25	30.25 ± 7.86^{ab}
3	41.77 ± 0.52	32.99 ± 3.89	28.61 ± 3.15	24.05 ± 2.45	28.55 ± 7.20^{bc}
4	38.34 ± 0.04	28.89 ± 0.70	28.23 ± 0.59	25.69 ± 0.70	27.60 ± 4.98^{c}
5	42.4 ± 1.13	35.49 ± 2.67	30.69 ± 2.81	26.96 ± 1.86	31.05 ± 6.28^{ab}
6	39.76 ± 2.35	31.90 ± 1.56	28.02 ± 3.07	27.73 ± 1.29	29.22 ± 5.38^{b}
Mean defoliation[2]	41.39 ± 2.56^{a}	33.13 ± 3.28^{b}	29.54 ± 3.17^{c}	26.77 ± 3.00^{d}	
Calahorra					
1	30.06 ± 0.94	33.31 ± 1.03	24.85 ± 1.77	23.62 ± 1.91	27.26 ± 4.12^{a}
2	30.48 ± 0.53	24.01 ± 0.81	22.30 ± 1.46	23.25 ± 0.10	23.19 ± 3.42^{bc}
3	30.57 ± 0.60	23.56 ± 2.26	21.72 ± 2.68	17.55 ± 1.25	20.94 ± 5.28^{d}
4	32.20 ± 3.18	25.41 ± 3.83	20.38 ± 1.07	19.88 ± 4.57	21.89 ± 5.96^{cd}
5	31.63 ± 1.37	25.13 ± 1.74	20.19 ± 1.48	19.98 ± 1.03	21.77 ± 5.06^{cd}
6	32.08 ± 2.57	26.47 ± 2.22	25.52 ± 2.34	21.76 ± 1.76	24.58 ± 4.30^{ab}
Mean defoliation[2]	31.17 ± 1.87^{a}	26.32 ± 3.47^{b}	22.46 ± 2.65^{c}	21.04 ± 2.93^{d}	

[1] Mean values in columns followed by the same letter do not differ significantly ($p < 0.05$). These values are the mean of slight, moderate and heavy defoliation levels yield values. [2] Mean values in rows followed by the same letter do not differ significantly ($p < 0.05$).

Table 4. Coefficients a and b of the regression equation $y = ax^2 + bx$ (x = % defoliation; y = % yield reduction) obtained for each time of defoliation in the two trials (R^2 = resolution coefficient of the equation)

Time of defoliation	BBCH phenological stage	San Adrián			Calahorra		
		a	b	R^2	a	b	R^2
1	105	-1.0×10^{-3}	+0.372	0.921[a]	$+7.0 \times 10^{-3}$	–0.409	0.976[a]
2	110	-2.3×10^{-3}	+0.634	0.945[a]	-4.0×10^{-3}	+0.660	0.987[a]
3	115	-1.9×10^{-3}	+0.603	0.955[a]	-1.0×10^{-3}	+0.571	0.956[a]
4	116	-2.0×10^{-3}	+0.549	0.998[a]	-2.0×10^{-3}	+0.645	0.948[a]
5	117/405	-1.0×10^{-3}	+0.516	0.974[a]	-5.0×10^{-3}	+0.849	0.975[a]
6	117/407	-5.0×10^{-3}	+0.800	0.985[a]	-2.0×10^{-3}	+0.484	0.972[a]

[a] $P < 0.001$.

quite high for all the equations and significant in all cases.

These equations can be used to estimate yield loss in each phenological stage with input of possible values of percentages of defoliation. Defoliation values of 20, 40, 60, 80 and 100% were substituted into the equations for the *x* variable to calculate the corresponding yield loss values for each phenological stage in each trial. The mean of yield loss of the two locations for each defoliation level-phenological stage were calculated and ploted in Figure 1 as yield loss curves.

In Figure 1 it can be observed that the highest yield loss, 44.2%, was reached at stage 3 for defoliation of 100%, according to the regression equations. When the defoliation treatments were applied in phenological stages earlier than stage 3, the yield loss was lower, even void, 0.8% for slight defoliation at phenological stage 1. Likewise, less yield loss was observed when defoliation was applied later than stage 3 (BBCH 115, 403).

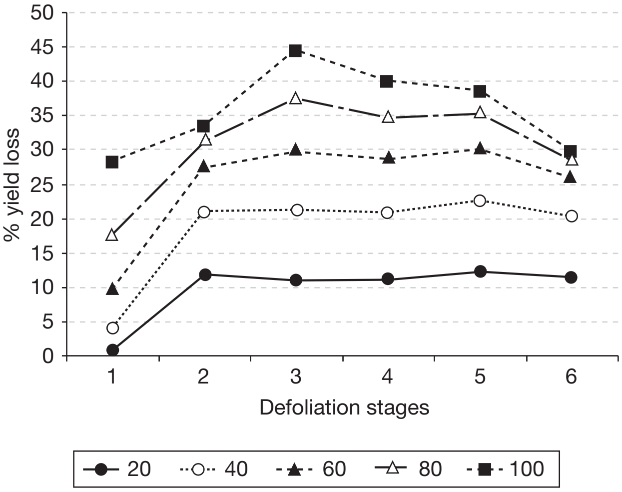

Figure 1. Yield reduction curves for leek, according to phenological stages and 20, 40, 60, 80 and 100% of defoliation. Phenological stages at defoliation correspond to: 1, 105; 2, 110; 3, 115/403; 4, 116/405; 5, 117/405 and 6, 117/407 on the BBCH scale.

Discussion

The behaviour of leek was different from the observed in other plants belonging to the same family, such as onion or garlic (Muro *et al.*, 1998b, 2000). In onion and garlic losses of 91% and 83% were reached respectively with 100% defoliation applied in the critical stages. This shows a greater sensitivity in onion and garlic compared to leek with regard to defoliations. The most critical phenological stage for leek was stage 3,when the plants have 15 leaves (115, BBCH scale) and the stem has reached 30% of its final diameter value (403 on the BBCH scale, see Table 1). This critical stage is physiologically similar to the critical stage of garlic and onion. For leek, it is the beginning of the thickening of the bulb (Muro *et al.*, 1998b, 2000). The low yield loss observed at earlier stages is due to the fact that the plant has sufficient time to recover from the damage suffered (Muro *et al.*, 1998b).

It is necessary to point out that the behaviour of defoliations was similar in leek and sugar beet (Muro *et al.*, 1998a). Both crops showed a similar sensitivity to defoliation throughout their crop cycle. On the other hand, the highest yield losses in sugar beet at the most critical phenological stage were 42.4% with 100% defoliation. Both crops had a similar agronomic behaviour in three aspects: (1) Along the cycle, they show a high capacity for developing new leaves; according to Hay and Kemp (1992) leek generates new leaves following a regular rhythm (plastochron of 100 degreedays) along its crop cycle. (2) Both species can expand the leaf blades from the portion remaining after mechanical damage occurs. (3) Both species can fill their underground reserve organ in a continuous way all along the cycle, because during their development no important physiological changes occur, such as flowering (for example maize, sunflower) or initiate bulb formation (for example: garlic, onion). In crops where key physiological changes can be observed, high defoliations (close to 100%) applied in these critical stages can cause 80-100% yield losses, because they are not capable, after sustaining the damage, to transfer their photosynthetic assimilates to generate new leaves.

The yield reduction equations shown in this study can be used to improve growth simulation models of the leek, in case of damage caused by biotic and abiotic stress like fungus attacks, insect attacks or hail.

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