Using Defoliation to Estimate Yield Losses in Cauliflower: Application in Hail Damage Assessment

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Abstract. Experiments were designed to assess the effects of defoliation and bending back petioles on the head mass of cauliflower (*Brassica oleracea* L. var. *botrytis* Alef. subvar. *cauliflora*, cv. Matra) in the Central Ebro Valley of Spain. Treatments were applied at seven different stages during the growth cycle. Defoliation reduced final head mass, the amount of the reduction increasing with level of defoliation. Bending back the petioles produced a loss in head mass intermediate between that caused by 33% and 66% defoliation. In all four trials, mass loss was highest when defoliation occurred at a head diameter between 20 and 38 mm. Neither defoliation nor bending of the petioles appeared to influence head induction or length of the production cycle. Maximum loss of head mass (85.4% to 64.9%) occurred when cauliflower was totally defoliated at a head diameter of 20–25 mm.

In the main cauliflower-producing regions of Spain, planting takes place in July and August, the months with the highest incidence of hail. Two to four hailstorms occur each year in the Central Ebro Valley, the main growing region in Spain (Diehl and Mateo-Box, 1978), with variable damage. The leaves of cauliflower plants provide good protection for the vegetative shoot apex in juvenile stages, the generative apex in the head induction stage, and the inflorescence in the head growth stage. Consequently, in most cases, direct damage to the head is minor and final hailstorm yield losses are indirect through lower final head mass (Muro et al., 1991).

Cauliflower crop insurance in Spain became available in 1984 (Ministerio de Agricultura Pesca y Alimentación, 1984) but, in 1992, only 263 ha were insured. One reason for this low level of insurance coverage is the lack of a damage rating standard (Ministerio de Agricultura Pesca y Alimentación, 1986a). Specifically, there are no data relating yield losses to time and severity of defoliation. Stewart et al. (1990) removed cauliflower foliage, but, in their study, defoliation was continuous and spanned several different stages, simulating constant destruction of leaf surface area by crop-destroying Lepidoptera larvae. We attempted to measure the effects of

single episodes of leaf destruction, simulating the effect of a hailstorm, on cauliflower production.

Table 1. Mean temperature and rainfall during the vegetative growth period of cauliflower in trials in 1989 and 1991.

	Year	Month				
		Aug.	Sept.	Oct.	Nov.	Dec.
Mean temperature (°C)	1989	22.5	19.1	15.0	9.6	6.5
	1991	23.6	21.0	16.4	9.7	3.8
Rainfall (mm)	1989	6	3	42	27	11
	1991	9	41	39	72	28

Table 2. Phenological stage of cauliflower and days from planting when defoliation was performed.

Defoliation stage	Trial 1 (1989)		Trial 2 (1989)	
	Phenological stage	Days from planting	Phenological stage	Days from planting
1	3 L ²	13	3 L	13
2	13 L	25	12 L	25
3	16 L	37	16 L	35
4	21 L + I ³ ϕ ⁴ <5 mm	50	20 L + I ϕ <5 mm	47
5	25 L + I ϕ $\approx$ 12 mm	62	26 L + I ϕ $\approx$ 6 mm	58
6	32 L + I ϕ $\approx$ 25 mm	78	31 L + I ϕ $\approx$ 22 mm	69
7	40 L + I ϕ $\approx$ 40–140 mm	88	40 L + I ϕ $\approx$ 27–38 mm	79
Defoliation stage	Trial 3 (1991)		Trial 4 (1991)	
	Phenological stage	Days from planting	Phenological stage	Days from planting
1	3 L	11	3 L	12
2	9 L	24	10 L	25
3	15 L	32	13 L	34
4	18 L	45	16 L	45
5	25 L + I ϕ < 5 mm	56	21 L + I ϕ < 5 mm	56
6	27 L + I ϕ $\approx$ 10 mm	67	24 L + I ϕ $\approx$ 5 mm	67
7	35 L + I ϕ $\approx$ 35 mm	81	35 L + I ϕ $\approx$ 20 mm	81

²Leaves.

³Inflorescence.

⁴Diameter of inflorescence.

The present study involved removing various amounts of foliage at different stages of plant growth as a means of collecting data on crop yield losses caused by the lost leaf area. The results may be used to estimate potential yield losses induced by leaf destruction due to hail as well as to other causes, such as insect pests, machinery, and contact herbicides.

Materials and Methods

Four trials were carried out, two in 1989 (trials 1 and 2) and two in 1991 (trials 3 and 4), at two locations 4 km apart in the Central Ebro Valley. According to the classification system of Papadakis (1960), the climate in the region is temperate Mediterranean. Table 1 presents the mean temperature and rainfall data for the study periods.

Plot soils were typical of the irrigated areas in the region and are designated Xeric torrifluent. There was a thick layer of alluvial calcareous loamy (trials 1 and 3) and silty-clay (trials 2 and 4) soil, pH = 7.5 to 8.

The cultivar Matra (Royal Sluis) was used in all trials. Bare-root seedlings with three to four leaves (>1 cm in stem diameter) were transplanted using a transplanting frame measuring 0.77–0.90 × 0.50–0.57 m. Planting was carried out between 3 and 11 Aug. in all trials. Furrow irrigation and the application of fertilizer and phytosanitary products were as customary for this crop in the region (Macua, 1989).

Four trials were performed. The experi-

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mental design of each was a split-plot with two factors. The main factor was the growth stage when damage took place (seven stages) and the secondary factor was the severity of the damage (five severity levels). Each of the four replicates consisted of seven randomly distributed plots (one for each stage) formed by five subplots (one for each severity level) containing 30 plants per subplot. A single severity level of damage was applied to each of the subplots.

Severity levels were: a) the removal of a portion of all leaf blades at one of four levels: 0% (control), 33%, 66%, or 100%, or b) bending back the upper two-thirds of the petiole of all leaves without removal of leaf area (used only in trials 1 and 2).

The defoliation method employed in the field was as follows. Several leaves were taken from some plants located outside of the experimental area and silhouetted using a photocopier. Leaf surface area was then measured and the leaf blade was divided into three parts of equal area by drawing two lines perpendicular to the midrib. Using the photocopies as models, the corresponding portions of the blades of all the leaves of all the plants in each subplot at the time of defoliation were re-

moved with scissors. All leaves that had separated, at the time of the treatment, from the apical leaves enfolding the terminal apex were removed. Defoliation was performed at various times and phenological stages of plant growth (Table 2). Stages were defined based on the number of leaves separated from the apical leaves, as well as on head diameter. Based on the cauliflower growth stages described by Rahn (1979), the first defoliation was performed during the juvenile stage, the following two defoliations during head initiation or induction, and the final four defoliations during head growth.

Harvesting was performed by hand in November and December when the cauliflower heads had attained maximum commercial size. Several harvests (*i*) were made. The weighted mean duration of the production cycle was calculated for each subplot using the expression:

$$\Sigma (\text{no. of heads harvested at day } i \times \text{days from planting to day } i) / \text{total no. of heads.}$$

The number of dead and deformed plants was counted before harvest in trials 1 and 2. The fresh mass and diameter of individual heads were measured after harvest (trials 3 and

4). Qualitative characteristics, such as structure, texture, color, shape, and curd defects, were evaluated according to the cauliflower quality standards (Ministerio de Agricultura Pesca y Alimentación, 1986b). Based on these standards, the heads were divided into two groups, commercial and noncommercial (diameter <11 cm and/or damaged heads). Each main plot contained a control subplot (0% defoliation). Percent fresh mass loss was calculated using the following equation:

$$\begin{aligned} \% \text{ Fresh mass loss} \\ &= \{ [\text{Comm. yield (control)} - \text{comm. yield (defoliated subplot)}] / \text{Comm. yield (control)} \} \times 100 \end{aligned}$$

Each trial yielded 16 pairs of values of percent mass loss/percent defoliation for each phenological stage in which defoliations took place (four defoliation levels $\times$ four replications each). Linear regression of these data on data of defoliation yielded good fits to the data, and the regressions were calculated without a constant term because the mass loss (function *y*) for a defoliation of 0% (variable *x*) is 0%. Damage caused by bending petioles was considered to be qualitatively different from defoliation damage, and the corresponding mass loss values were not included in these calculations.

The results of the four trials were grouped by standardized phenological stage because the seven defoliation episodes in each of the trials did not take place at identical stages in each trial (Table 2). To this end, nine phenological stages were redefined and designated using Roman numerals (Table 3). The phenological stage for each defoliation episode in each trial (Table 2) was then assigned to the corresponding redefined phenological stage in Table 3. After the appearance of the curd, head diameter was the primary criterion for redefining the phenological stages (Table 3).

To simplify the data presentation and avoid the need to report partial data for each trial, a

Table 3. Redefinition of standardized phenological stages of cauliflower (Roman numerals) used to regroup the defoliation episodes in the four trials.

Stage	Phenological stage	Trial number (defoliation stage) ^c
I	3 L ^b	1 (1), 2 (1), 3 (1), 4 (1)
II	9–10 L	3 (2), 4 (2)
III	12–14 L	1 (2), 2 (2), 4 (3)
IV	15–18 L	1 (3), 2 (3), 3 (3, 4), 4 (4)
V	20–25 L + I ^a ϕ < 5 mm	1 (4), 2 (4), 3 (5), 4 (5, 6)
VI	25–27 L + I ϕ = 5–15 mm	1 (5), 2 (5), 3 (6)
VII	31–35 L + I ϕ = 20–25 mm	1 (6), 2 (6), 4 (7)
VII	35–40 L + I ϕ = 27–38 mm	2 (7), 3 (7)
IX	40 L + I ϕ = 40–140 mm	1 (7)

^aNumber of trial (bold number) and defoliation stage (number in parentheses) (from Table 2).

^bLeaves.

^cInflorescence.

^dDiameter of inflorescence.

Table 4. Three-way (split-split-plot) analysis of variance for mean head fresh mass, mean cycle length, head diameter, and percent dead or deformed plants in cauliflower.

Source	df	Head fresh mass				df	Cycle length			
		SS	% SS ^a	F ^b			SS	% SS	F	
Stage	8	1,488,270	7.3	7.2 ^{ns}		8	19,284	31.8	50.5 ^{ns}	
Injuries	4	14,111,099	69.1	185.8 ^{ns}		4	1,860	3.0	23.9 ^{ns}	
Stages $\times$ injuries	31	1,484,411	7.3	2.5 ^{ns}		31	11,647	19.2	19.3 ^{ns}	
Trial	3	1,265,690	6.2	8.9 ^{ns}		3	23,776	39.2	99.1 ^{ns}	
Stage $\times$ trial	14	134,759	0.7	0.4 ^{ns}		14	0	0.0	0.0 ^{ns}	
Injuries $\times$ trial	10	722,888	3.5	3.8 ^{ns}		10	3,774	6.2	19.4 ^{ns}	
Stage $\times$ injuries $\times$ trial	47	667,182	3.3	0.8 ^{ns}		47	0	0.0	0.0 ^{ns}	
Blocks	3	534,653	2.6	3.8 ^{ns}		3	349	0.6	1.5 ^{ns}	

Source	df	Diameter				df	% Dead or deformed plants			
		SS	% SS	F			SS	% SS	F	
Stage	7	28.9	7.7	7.9 ^{ns}		7	4,476	15.3	9.0 ^{ns}	
Injuries	3	286.8	76.8	104.6 ^{ns}		4	2,404	8.2	11.1 ^{ns}	
Stage $\times$ injuries	21	26.4	7.1	1.4 ^{ns}		28	6,820	23.3	4.5 ^{ns}	
Trial	1	12.6	3.4	2.3 ^{ns}		1	6,237	21.3	134.0 ^{ns}	
Stage $\times$ trial	3	0.0	0.0	0.0 ^{ns}		5	687	2.3	1.9 ^{ns}	
Injuries $\times$ trial	3	1.9	0.5	0.7 ^{ns}		4	2,083	7.1	9.7 ^{ns}	
Stage $\times$ injuries $\times$ trial	9	8.0	2.1	1.0 ^{ns}		20	6,111	20.9	5.7 ^{ns}	
Blocks	3	9.0	2.4	0.5 ^{ns}		3	445	1.5	3.2 ^{ns}	

^a% SS = (Partial SS/total SS) $\times$ 100.

^bF probability.

^{ns}, ^{ns} Nonsignificant or significant at $P \leq 0.01$, respectively.

three-way analysis of variance (ANOVA) was run on the mean values using the factors trial, stage when damage occurred, and type of damage. The structure of the combined data matrix reflected the split-plot structure of the experimental design for the two last-mentioned factors in each trial.

The SPSS V.6.1.3. program was used for data analysis.

Results and Discussion

Following the proposal of Little (1981) for interpreting factor analysis results, the ANOVA (Table 4) contains a column (% SS) in which the relative contribution of factors and interactions is expressed as a percentage of total (SS). Variability among trial plots fluctuated widely from 3.4% to 39.2% (column % SS for the factor "trial," Table 4), depending upon the parameter measured. This finding is normal for field trials (Austin, 1993), and the four

trials were carried out in four different sites in two different years.

Yield loss was the result of three components: a) reduction in plant number, b) production of a deformed head or no head at all, and c) lower unit mass of harvested heads. The first two effects are direct forms of production loss that are readily assessable by preharvest sampling. The third is an indirect form of damage, and is much more difficult to assess without yield loss tables or data relating the extent of defoliation to the phenological growth stage when the damage occurs. Direct damage was measured only in trials 1 and 2 (Table 5), and differed in the two trials (data not shown). There were no significant differences between the factors and their interactions in trial 1, whereas in trial 2 there were significant differences for defoliation stage (between stages III and IV vs. remaining stages), type of damage (100% defoliation vs. the remaining treatments), and the interactions stages $\times$ damage

(basically 100% defoliation $\times$ stages I, III, and IV). Death of plants was much more important than head deformation, which was much more common in the plots in which the petioles were bent back. Lower soil fertility in trial 2 may have adversely affected rooting, making the plants more sensitive to the stress of the earliest defoliations and producing a higher level of mortality.

The data for mean fresh mass of commercially acceptable heads harvested (Table 5) were much more uniform among the trials (6.2% SS for the factor trial, Table 4). Damage type displayed the highest variability (69.1% SS, Table 4); the effects of defoliation stage and stage $\times$ injuries interaction were smaller. The LSD test detected differences among all types and levels of defoliation. Stages VIII, VII, and VI, in that order, presented the largest number of significant differences with respect to the other stages. The effect of stage $\times$ injuries interaction was much smaller and was

Table 5. Effects of defoliation and of bending petioles of cauliflower on plant survival or deformation, head mass, head diameter at harvest, and production cycle length in days.

Type and level of damage		Phenological stages at time of treatment										
		I	II	III	IV	V	VI	VII	VIII	IX	Mean	No. of samples
Percentage of dead or deformed plants (Trials 1 and 2)												
Defoliat.	0%	5.8	---	2.7	7.6	12.9	5.8	2.7	17.0	8.9	7.9	56
Defoliat.	33%	10.7	---	11.6	13.8	8.0	12.0	12.5	7.1	4.5	10.0	56
Defoliat.	66%	9.8	---	13.4	13.4	3.6	8.0	1.8	11.6	6.2	8.5	56
Defoliat.	100%	26.3	---	31.7	20.1	2.2	6.2	8.5	15.2	3.6	14.2	56
Bent petioles		13.4	---	17.4	27.7	8.5	11.6	7.6	13.4	3.6	12.9	56
Mean		13.2	---	15.4	16.5	7.0	8.7	6.6	12.9	5.3		
Sample number		40	---	40	40	40	40	40	20	20		
MSE' (stage, $P \leq 0.95$) = 71.04 ; critical value of $t = 2.03$; LSD = 3.82												
MSE (damage, $P \leq 0.95$) = 53.85; critical value of $t = 1.97$; LSD = 2.74												
MSE (stage $\times$ damage, $P \leq 0.95$) = 53.85; critical value of $t = 1.97$; LSD (n = 4) = 10.22; LSD (n = 8) = 7.23												
Head mass (g) (Trials 1-4)												
Defoliat.	0%	840.6	883.4	799.4	910.6	879.8	851.7	950.7	898.9	890.0	878.3	104
Defoliat.	33%	809.2	779.2	844.7	797.1	695.7	646.5	609.1	584.9	827.0	732.2	104
Defoliat.	66%	724.9	630.7	704.3	613.0	534.0	449.5	439.6	446.1	531.2	563.7	104
Defoliat.	100%	505.8	393.8	441.7	395.1	368.5	311.0	300.0	274.4	341.6	370.2	104
Bent petioles		746.8	---	673.8	563.4	612.9	672.1	565.2	589.7	701.4	640.7	56
Mean stages		725.5	671.8	692.8	655.8	618.8	586.2	572.9	558.8	658.2		
Sample number		72	32	56	72	72	56	56	36	20		
MSE (stage, $P \leq 0.95$) = 25710.2; critical value of $t = 2.00$; LSD = 68.21												
MSE (damage, $P \leq 0.95$) = 18983.6 ; critical value of $t = 1.97$; LSD = 40.71												
MSE (stage $\times$ damage, $P \leq 0.95$) = 18983.6 ; critical value of $t = 1.97$; LSD (n = 4) = 191.93; LSD (n = 8) = 135.71; LSD (n = 12) = 110.8; LSD (n = 16) = 95.96												
Head diameter (cm) at harvest (Trials 3-4)												
Defoliat.	0%	15.7	15.8	15.5	15.0	15.3	14.9	16.1	15.7	---	15.5	48
Defoliat.	33%	15.3	15.3	14.7	15.4	14.3	13.8	13.5	13.7	---	14.7	48
Defoliat.	66%	14.5	13.7	14.9	14.1	13.3	13.2	13.2	12.9	---	13.8	48
Defoliat.	100%	12.8	12.2	12.6	11.9	12.3	11.5	12.2	11.3	---	12.2	48
Mean stages		14.6	14.3	14.4	14.1	13.8	13.4	13.8	13.4	---		
Sample number		32	32	16	32	32	16	16	16	---		
MSE (stage, $P \leq 0.95$) = 0.5227; critical value of $t = 2.04$; LSD = 0.45208												
MSE (damage, $P \leq 0.95$) = 0.91404; critical value of $t = 1.98$; LSD = 0.3868												
MSE (stage $\times$ damage, $P \leq 0.95$) = 0.91404; critical value of $t = 1.98$; LSD (n = 4) = 1.34; LSD (n = 8) = 0.95												
Production cycle length (days) (Trials 1-4)												
Defoliat.	0%	130.6	131.6	133.9	130.5	131.6	129.3	130.5	129.1	125.3	130.3	104
Defoliat.	33%	131.0	132.6	131.4	131.0	129.7	124.1	126.9	126.4	119.3	128.1	104
Defoliat.	66%	132.6	137.0	134.7	133.6	128.7	120.4	120.1	121.4	113.6	126.9	104
Defoliat.	100%	138.7	152.7	139.3	134.2	123.6	113.9	108.7	110.9	97.8	124.8	104
Bent petioles		127.9	---	129.0	133.0	122.4	122.5	115.8	130.3	105.9	123.4	56
Mean stages		132.2	138.5	133.7	132.5	127.2	122.0	122.9	122.9	112.4		
Sample number		72	32	56	72	72	56	56	36	20		
MSE (stage, $P \leq 0.95$) = 47.74; critical value of $t = 2.00$; LSD = 2.94												
MSE (damage, $P \leq 0.95$) = 19.44; critical value of $t = 1.97$; LSD = 1.30												
MSE (stage $\times$ damage, $P \leq 0.95$) = 19.44; critical value of $t = 1.97$; LSD (n = 4) = 6.14 ; LSD (n = 8) = 4.34; LSD (n = 12) = 3.55; LSD (n = 16) = 3.07												

^aMean square error.

only significant in one of the four trials when each trial was analyzed separately (data not shown). Bending back the petiole reduced mass to a value intermediate between those for the 33% and 66% defoliations.

Results for head diameter (Table 5) were closely associated with the results for head mass. On the whole, defoliation during the final stages lowered both the mean diameter and the mean mass of heads more than did defoliation in earlier stages, in agreement with the findings of Stewart et al. (1990). This was partially the result of both the loss of leaf surface for photosynthesis and the need to advance the harvesting date. Depending on the extent of defoliation, heads were subject to more rapid deterioration in response to abiotic and biotic factors than were those protected by the leaves.

Length of the production cycle varied widely among trials (39.2%, Table 4). The head induction stage in cauliflower, which extends from emergence of leaves no. 16–18 to the appearance of the bud, requires a certain number of hours below a temperature threshold, hence the lower the temperature, the shorter this stage (Booij and Struik, 1990). The induction stage in the trials took place in late August and early September. Accumulation of hours below the threshold is particularly dependent upon night temperatures. For that reason, head induction was slower in Aug. and Sept. 1991, when temperatures were higher than in 1989 (Table 1) and the growing cycle was longer (134.0 vs. 122.2 d, respectively). Defoliation stage was the second most important factor affecting variability of cycle length (31.8% SS, Table 4). In three of the four trials, defoliation before appearance of the inflorescence did not significantly alter cycle length with respect to the control group (data not shown), suggesting that the damage before budding did not significantly interfere with the budding process (Booij and Struick, 1990; Rahn, 1979). From that time on (stage V), defoliation significantly shortened cycle length (Table 5).

The interaction effect was the third source of variation (19.3% SS, Table 4), particularly because of the shortening of the cycle produced by 100% defoliation in the last three stages. Stewart et al. (1990) did not record any change in cycle length based on the type or extent of defoliation, but the defoliation types and harvest criteria they used make comparison difficult.

The normal coloration of the control heads was white or ivory. Defoliation tended to change the color quickly to a yellowish-white.

Table 6. Values of the constant "a" for the regression equations ($y = a \cdot x$) for each phenological stage in cauliflower ($x = \% \text{ defoliation}$; $y = \% \text{ yield loss}$).

Phenol. stage	Trial 1		Trial 2		Trial 3		Trial 4	
	a	r^2	a	r^2	a	r^2	a	r^2
I	0.178	0.34 [*]	0.539	0.73 ^{***}	0.350	0.45 ^{***}	0.338	0.55 ^{***}
II	---	---	---	---	0.456	0.76 ^{***}	0.488	0.69 ^{***}
III	0.260	0.33 [*]	0.623	0.91 ^{***}	---	---	0.427	0.78 ^{***}
IV	0.386	0.72 ^{***}	0.636	0.71 ^{***}	0.514 [†]	0.67 ^{***}	0.440	0.78 ^{***}
V	0.534	0.78 ^{***}	0.653	0.83 ^{***}	0.535	0.80 ^{***}	0.585 [†]	0.90 ^{***}
VI	0.587	0.86 ^{***}	0.793	0.89 ^{***}	0.608	0.88 ^{***}	---	---
VII	0.658	0.91 ^{***}	0.854	0.88 ^{***}	---	---	0.649	0.90 ^{***}
VII	---	---	0.765	0.87 ^{***}	0.644	0.91 ^{***}	---	---
IX	0.567	0.74 ^{***}	---	---	---	---	---	---

^{*}Coefficient of determination.

[†]Equation based on the results obtained by combining two defoliation stages into a single standardized phenological stage (see Table 3: stage IV, trial 3, and stage V, trial 4).

^{***}Significant at $P \leq 0.05$ or 0.01, respectively.

This tendency was more pronounced the greater the extent of defoliation and the later the stage at which defoliation occurred.

All the heads collected fit the classification "firm and compact" as defined by the quality standards (Ministerio de Agricultura, Pesca y Alimentación, 1986b), though heads from plants defoliated in the later stages were more compact because harvesting had to be advanced. In the plants in which the petioles had been bent back, the heads were elongated and, in some cases, deformed. A few cases of bractiform leaves among the florets of the inflorescence were recorded for plants defoliated in stages III and IV, and were more evident the greater the extent of defoliation. Defects, such as sunburn, frost damage, appearance of warts, and attack by snails or slugs, were more frequent in plants that were extensively defoliated late in the season.

The method described above was used to calculate regression equations for the defoliation stages in each trial, yielding the percent mass loss as a function of the extent of defoliation (Table 6). These equations can be used to assess indirect damage to cauliflower crops that have been defoliated, for instance, by hail.

Final head mass decreased with, and was greater, as defoliation was delayed up to stages VII and VIII, with a lessening at stage IX. Maximum loss (85.4% to 64.9%) was induced by total defoliation in stage VII, when the inflorescence was 20 to 25 mm in diameter. Mass loss occurring after head formation was due to reduced photosynthetic capacity and protection against biotic and abiotic agents. We conclude that harvest date should be advanced, when heads are small, in order to avoid these problems.

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