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SUPPLEMENTAL POLLINATION – INCREASING OLIVE (*OLEA EUROPAEA*) YIELDS IN HOT, ARID ENVIRONMENTS

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SUMMARY

In general, olive trees are self-compatible, but under some climatic conditions a number of cultivars have demonstrated problems with pollination and fruit set. The Manzanillo cultivar is usually self-pollinating, but under hot conditions its pollen develops slowly, resulting in little or no fertilization. Trials were carried out in two hot, arid ecosystems (Arid Chaco in La Rioja, Argentina and Sonoran Desert in Arizona, USA) to determine if supplemental pollination of a Manzanillo cultivar has the potential to increase yields, and to assess the effectiveness of three different cultivars as sources of pollen. Branches that received supplemental pollination produced 21 % more total olives than the control. In Arizona, total olive and shotberry (unpollinated olive) production were significantly different between treatments. Branches that received supplemental pollination produced 98 % more olives, and had 58 % fewer shotberries than did branches in the control rows. Significantly more olives were produced on branches pollinated with Sevillano and Arbequina pollen, compared with those pollinated with Ascolano pollen and with the control.

INTRODUCTION

Olives (*Olea europea*) probably originated in Asia Minor, six thousand years ago. In the fourteenth century BC, olive trees were spread by Phoenicians to the Greek Islands and the Hellenic Peninsula. By the sixth century BC, olives had spread further into the Mediterranean basin (Blazquez, 1996).

Thousand-year-old olive trees have been found in Israel, Palestine and Spain, as well as in other Mediterranean areas (Mas-Candela, 1991; Martin, 1994). Today, table olives and olive oil are very important to the agro-industrial sectors of these countries. Spain is the largest producer of olives, followed by Italy and Greece, with these countries producing 60 % of the world's olives. Outside the Mediterranean basin, Argentina and the United States are the major olive producers (Connell, 1994).

The olive is a monoecious plant, having both perfect and imperfect flowers (Martin *et al*., 1994; Rallo, 1997). Thus, either self-pollination or cross-pollination can be found in olives, with wind being the main pollinating agent. Traditionally in Spain, olives have been managed as self-compatible trees, and almost no Spanish fields include other cultivars as pollinators (Cuevas *et al*., 2001). New plantings are generally established using single cultivars.

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In general olive trees are self-compatible, but in some climatic situations a number of cultivars have demonstrated problems with pollination and fruit set. Manzanillo, one of the most valuable olive cultivars, and the one that is most widely cultivated around the world, is an example. Generally the Manzanillo cultivar is self-pollinating, but under hot conditions its pollen grows slowly, resulting in little or no fertilization (Martin *et al*., 1994; Lavee *et al*., 2002).

Initial olive commercialization efforts took place in areas with climates similar to where they originated, such as in California (USA), Western Australia and Baja California (Mexico). However, in the middle of the twentieth century, commercial plantations began in environments very different from the Mediterranean basin, such as the Arid Chaco in Argentina, the Sonoran Desert in the USA and the Altar Desert in Mexico (Ayerza and Sibbet, 2001). Early in their life cycle, these olives started to show problems with fruit set and yield, with plant growth and metabolism being profoundly affected by the very different environmental conditions found in these regions, compared with the Mediterranean climate (Ayerza and Sibbet, 2001).

The best Mediterranean olive growing areas are characterized by mild, rainy winters and long, warm, dry summers (Steward, 1971; Noggle and Fritz, 1983; Fitter and Hay, 1987; Sibbett and Osgood, 1994; Navarro and Parra, 1997; Ayerza and Sibbett, 2001). Extreme temperatures affect the reproductive cycle of the olive (Hartmann, 1953; Bradley *et al*., 1961; Griggs *et al*., 1975; Guerrero, 1991; Sibbett and Osgood, 1994; Lavee, 1996; Tous-Marti and Ferguson, 1996). Cross-pollination improves fertilization and fruit set under hot environments, as well as in years of poor flower quality (Ghrisi *et al*., 1999; Cuevas *et al*., 2001). The need for cross-pollination exists when air temperatures during olive bloom exceed 30 °C (Rallo, 1997). Another problem in warm, dry ecosystems, such as the Arid Chaco of Argentina, is a very short vernalization period (Ayerza and Sibbett, 2001). This increases incompatibility of self-pollination for many cultivars, including Manzanillo, but it has not been shown to affect open-pollination (Lavee *et al*., 2002).

High temperatures during olive flowering increase pollen incompatibility. Pollen tubes of the same cultivar frequently become blocked between the stigma and embryo sac under these conditions. As air temperatures increase from 26.7 to 32.2 °C, pollen tubes from foreign olive cultivars have been found to be more aggressive, and hence can reach the embryo sacs before they degenerate (Bradley *et al*., 1961).

Since Manzanillo and Sevillano cultivars are compatible, including Sevillano trees as pollinators in Manzanillo groves has become a general practice in California. Research has demonstrated that dissemination of olive pollen is most effective within a radius of 30 m of pollinators (Sibbett and Osgood, 1994). However, under hot arid conditions the distance for effective pollination is reduced (G. Vega, personal communication, 2002). Another limitation under hot and dry conditions is that Manzanillo and Sevillano cultivars bloom simultaneously for only a few days.

Increasing the number of pollinator trees in a grove could solve some of these problems, but also has negative economic implications. First, it reduces the number of olive-producing trees per hectare, and secondly it introduces a considerable delay in improving yields in established monocultivar groves, which are the majority of bearing

Table 1. Mean climatic data, by season, for the Argentina and Arizona sites where supplemental pollen was applied to olive trees.

	Autumn†			Winter‡			Spring§			Summer¶		
	Air temperature (°C)		Total rainfall	Air temperature (°C)		Total rainfall	Air temperature (°C)		Total rainfall	Air temperature (°C)		Total rainfall
Site	Max	Min	(mm)	Max	Min	(mm)	Max	Min	(mm)	Max	Min	(mm)
Arizona	36	0	43	27	0	61	41	8	14	42	17	56
La Rioja	38	−3	16	39	−10	8	46	3	110	46	8	173

† Autumn. Argentina: 21 March to 20 June. Arizona: 21 September to 20 December.
‡ Winter. Argentina: 21 June to 20 September. Arizona: 21 December to 20 March.
§ Spring. Argentina: 21 June to 21 September. Arizona: 21 March to 20 June.
¶ Summer. Argentina: 21 December to 20 March. Arizona: 21 June to 21 September.

fields (Ayerza and Sibbett, 2001). Applying supplemental pollen is an alternative solution, which could immediately improve fruit set and increase yields in hot, arid olive-producing areas.

Supplemental pollination has been shown to work in olive groves in California (G. Sibbett, personal communication, 1992). No information was available, however, on the effectiveness of such a procedure under the dry Chaco or Sonoran Desert environments where many new plantations are located. This paper reports on trials carried out in commercial fields to determine if supplemental pollination of a Manzanillo cultivar in these ecosystems increases yields, and also discusses the effectiveness of three different cultivars as sources of pollen for use on Manzanillo.

MATERIALS AND METHODS

Test locations

The trial in the Sonoran Desert was conducted in 1998 in a commercial olive grove located on the Gila River Indian Reservation in Arizona at (33°04′N; 111°58′W, alt 361 m asl). The Sonoran desert climate is typically desert with precipitation being deficient throughout the year, but particularly so in April, May and June. The wettest months are normally July and August.

The trial in the Arid Chaco was conducted in 2002 in a commercial grove owned by Nevado del Famatina S.A. The fields are located in the Province of La Rioja, Argentina, (29°23′S; 66°49′W, alt. 430 m asl). The Arid Chaco climate has rains in the summer and dry winters. Strong southern and northern winds are typical. Additional climatic details for these two areas are provided in Table 1.

Supplemental pollination trials

The trials were carried out in fields that had been planted with pure Manzanillo cultivar cuttings, rooted by the Don DeLeonardis Nursery, Visalia, California. The genetic material came from the DeLeonardis farm.

Table 2. Maximum, minimum, mean daily air temperatures (24 hours) and mean wind speed on the days (October in Argentina, July in Arizona) when supplemental pollen was applied to olive trees as recorded by an on-farm automated weather station.

	Argentina			Arizona			Argentina		Arizona	
	Air temperature (°C)						Wind (km h^{-1})			
Day	Max	Min	Mean	Max	Min	Mean	Max	Mean	Max	Mean
1	40.8	18.4	30.1	29.6	14.1	22.8	27.4	8.3	31.7	9.6
2	31.0	12.0	25.7	29.6	12.5	22.2	25.7	8.9	33.3	9.8
3	24.8	9.8	24.6	–	–	–	37.0	9.2	–	–

The La Rioja experiment utilized two fields (70 ha each) containing seven-year-old trees planted in rows 7 m apart, with a 6 m in-row spacing. The rows were oriented in an east–west direction. Pollen was applied by machine along both sides of eight rows. Three applications, one per day on three consecutive days, were made (150 g ha^{-1} for the first application, and 200 g ha^{-1} for each of the other two applications). Pollen was applied between tree number 9 and number 40 in one field, and between tree number 20 and number 51, in the second field. The layout of each field was as follows: four border rows, two control rows, five buffer rows, two test rows, four buffer rows, two control rows, four buffer rows, two test rows, four buffer rows, two control rows and four border rows.

The Arizona trial was conducted in a 135 ha field containing six-year-old trees planted in rows spaced 6.1 m apart, with an in-row spacing of 6.7 m. The rows were oriented in a north–south direction. Pollen was applied by machine along both sides of 20 rows, in two applications, one per day on two consecutive days (74 g ha^{-1} for each application). Field layout was as follows: two border rows, five test rows, 32 control rows, five test rows, 32 control rows, five test rows, 32 control rows, five test rows and seven border rows.

Both experiments utilized pollen obtained from Dr. T. Ferrari, Bakersfield, California, USA. The Sevillano pollen applied in La Rioja had a viability of 57.5 million viable pollen grains g^{-1}; pollen viability for the Arizona trial was not recorded, but in general it has ranged from 60 to 90 million viable pollen grains g^{-1} (T. Ferrari, personal communication, 2002). Pollen application took place between 07:00 hours and 11:00 hours in La Rioja, and between 7:00 hours and 9:00 hours in Arizona. Temperature and wind data for the application days are shown in Table 2.

The applicator consists of an electrically driven metering screw, which is located at the bottom of a small hopper. The speed of rotation of the screw can be changed to increase or decrease the flow rate of pollen out of the hopper. After exiting the screw assembly, the pollen enters a tube connected to a blower. The airstream directs the pollen up a tube having openings, at several different points along its length, through which the pollen is dispersed. The applicator was mounted on a medium-sized tractor for the La Rioja experiment, and on an all-terrain vehicle for the Arizona trial. Both pollen applicators were modified versions of the design developed by T. Ferrari, Bakersfield, California.

Evaluations to determine effectiveness were made 93 days after the first pollen application in La Rioja, and 96 days after the first application in Arizona. In La Rioja, for each treatment, 30 trees from each pair of rows (a total of 120 trees per treatment) were selected at random. On each tree, one branch (approximately 0.60 m long) on the northern side and one on the southern side was selected at random for sampling and the number of olives and shotberries on each was counted. In Arizona, five trees from each treated row were selected at random, and on each tree, one branch (approximately 0.60 m long) on the eastern side and one on the western side was selected at random for similar counts. A total of 240 and 200 branches per treatment were selected for La Rioja and Arizona, respectively.

Compatibility test

Pollen from Sevillano, Ascolano and Arbequina cultivars was applied to Manzanillo trees in the La Rioja field. The Sevillano pollen was the same as that used in the supplemental pollination experiment, with the Ascolano pollen also being obtained from Dr. T. Ferrari. The Arbequina pollen was mechanically harvested from trees growing in a nearby field. Viability was measured at 57.5, 94.2 and 93.6 million viable pollen grains g^{-1} for the Sevillano, Ascolano and Arbequina pollen respectively.

Three trees were selected at random from the outside row on which pollen was applied in the supplemental pollination experiment, between trees numbered two and seven (outside the range where pollen was mechanically applied). Three branches from the southern side of each tree were selected at random, and each was pollinated with one of the three pollen sources (a total of 24 branches per treatment). Pollinated branches were tagged with different coloured tapes, according to pollen source. The process was repeated for three consecutive days, with one tape, two tapes and three tapes used to identify application dates. Application was made by blowing pollen over the flowers from a distance of approximately 300 mm. For the control, data from the control rows in the supplemental pollination trials were used, but only branches on the south side of the trees were considered. As for the supplemental application trials, the number of olives and shotberries per branch were counted on each of the tagged branches. Date and time of pollen application, as well as date when the counts were made, were the same as in the supplemental pollination trial.

Statistical analysis

Each variable was compared using the Generalized Linear Model analysis of variance technique to assess differences. (SAS Institute, Inc., 2002).

RESULTS

Supplemental pollination trials

Table 3 summarizes the results for both trials. In La Rioja (Argentina), total olive production and olive production on the south side of the rows were significantly greater ($p < 0.05$) in the treated rows than in the control. Sampled branches that received supplemental pollination produced 21 % more total olives and 35 % more olives on

Table 3. Comparison of the number† of olives, shotberries and percentage fruit set between olive trees which had supplemental pollen applied (pollinated) and those which were naturally pollinated (control).

Treatment	Olives	Shotberries	Set (%)	Olives	Shotberries	Set (%)	Olives	Shotberries	Set (%)
	Total			South side			North side		
Argentina									
Pollinated	10.3	5.8	75	12.7	6.3	78	7.8	5.4	72
Control	8.5	5.6	74	9.4	6.5	73	7.5	4.8	74
s.d.	8.21	12.76	31.5	8.92	15.99	30.8	7.08	8.36	32.1
	Total			East side			West side		
Arizona									
Pollinated	6.9	1.7	87.5	6.1	2.1	86	7.9	1.2	89.4
Control	3.5	3.8	68.9	3.5	5.0	63	3.2	2.6	74.6
s.d.	5.91	6.11	31.5	4.21	7.34	9.4	7.21	4.44	28.70

† Mean number for 0.60 m branch length.

Table 4. Comparison between row sides of the number† of olives, shotberries and percentage fruit set for olive trees which had supplemental pollen applied (pollinated) and those which were naturally pollinated (control).

	Pollinated			Control		
Treatment	Olives	Shotberries	Set (%)	Olives	Shotberries	Set (%)
Argentina						
South side	12.7	6.2	78	9.4	6.5	73
North side	7.8	5.4	71	7.5	4.8	74
s.d.	9.46	15.41	31.0	7.01	10.29	31.9
Arizona						
East side	6.1	2.1	86	3.5	5.0	63
West side	7.9	1.2	89	3.2	2.6	74
s.d.	7.10	4.55	25.43	2.65	7.55	36s

† Mean number for 0.60 m branch length.

the south side of the row, than did sampled branches in the control. No significant difference in production on the north side of the rows was found. Total south and north shotberry production were similar. No differences in fruit set percentage, calculated as number of olives divided by sum of shotberries and olives, were found between treated and untreated rows in La Rioja.

In the Arizona trial, total olive and shotberry production were significantly different ($p < 0.05$) between treated and untreated rows. Sampled branches that received supplemental pollination produced 98 % more olives and 57 % fewer shotberries than did sampled branches in the control rows.

The comparison of olive and shotberry production, as well as fruit set percentage, between tree sides within treatments at each location is presented in Table 4. In La Rioja, significantly ($p < 0.05$) fewer olives were found on the north side of the trees, compared with the south side. The absence of a significant difference in olive

Table 5. Comparison of the number† of olives, shotberries and percentage fruit set between pollen sources when applied to Manzanillo olive trees in October in Argentina.

Pollen source	Olives	Shotberries	Fruit set (%)
Sevillano	16.2	1.4	92
Arbequina	15.8	1.2	95
Ascolano	11.5	1.3	93
Control	8.9	5.8	73
s.d.	8.90	9.31	29.5

† Mean number for 0.60 m branch length.

production on the north side of the trees in La Rioja negatively influenced total olive production. Branches from the south side showed an increase in production of 35 %, compared to an overall increase of 21 %. No differences in olive production between the east and west sides, within treatments, were detected in Arizona.

No differences in percentage fruit set were detected between tree sides at either location. The only difference in shotberry counts that was detected between row sides was found in the control treatment in Arizona, where east side branches had more shotberries than those on the west side.

Compatibility test

Table 5 presents the results for the branches that were hand-pollinated using Sevillano, Ascolano and Arbequina pollen. Application date was not significant for any pollen type. Significantly more olives were produced on the branches pollinated with Sevillano and Arbequina pollen, compared with those pollinated with Ascolano pollen and with the control. No significant differences in shotberry production among branches pollinated with Sevillano, Ascolano and Arbequina pollen were detected. All of the branches that received supplemental pollen produced significantly fewer shotberries than did the control.

Fruit set percentage was higher for the branches that were hand pollinated, regardless of pollen source, compared with the control (Table 5). No differences in fruit set percentage were found among branches receiving Sevillano, Ascolano or Arbequina pollen.

DISCUSSION

Fruit set measurements taken no earlier than 45–60 days following pollination provide more reliable crop yield data than do earlier measurements because of the greatly reduced effect of abscission and other causes of fruit drop (Rallo *et al*., 1981). Ghrisi *et al*. (1999) found no differences in fruit drop behavior for five olive varieties for either self-pollination or cross-pollination. They reported that heavy fruit drop occurred during the first 20 days after fruit set, then decreased to almost nothing 45 days after fruit set. Thus in order to obtain more reliable crop yield estimates for the current trials, a 90 day sampling period was chosen.

Supplemental pollination trial

The increase in olive production found in this trial is similar to other studies conducted in California in which supplemental pollen has been applied in commercial groves (Sibbett, personal communication, 1998). The results also agree with those from an experiment conducted in Marrakech, Morocco (Ghrisi *et al*., 1999), and with those from a study in Spain (Cuevas *et al*., 2001), in which increases in olive production in artificially pollinated groves varied among locations. In both cases Manzanillo was one of the cultivars evaluated. Lavee *et al*. (2002) studied cross-pollination in a number of olive cultivars, including Manzanillo, over a period of 12 years. They reported that the level of fruit set within cultivars was location-dependent, and year-dependent. In the latter two experiments as data were collected 30 and 12–21 days following full bloom respectively, differences in results between these trials and those reported here could have arisen. The longer time period between pollination and data collection in the La Rioja/Arizona trials most likely masked the fruit loss by abscission that Cour and Villemur (1985) have shown takes place in olives.

The positive response to pollen application was apparent in the increase in olive production at both sites (Table 3). Even though more than double the amount of the pollen was applied in La Rioja than in Arizona, the magnitude of the increase in production in Arizona was four times that in La Rioja. The difference may have been due to the maximum temperatures reached during the time pollen application took place. For olive trees, optimum flowering occurs when the daily maximum air temperature fluctuates between 16–19 °C, and the daily minimum is between 2–4 °C (Martin *et al*., 1994). High temperatures during flowering adversely affect bloom development, pollination, and fruit set (Lavee, 1996; Tous Marti and Ferguson, 1996). In La Rioja, maximum air temperatures on the first two application days were 40.8 and 31.0 °C, compared to 29.6 °C in Arizona (Table 2). As was demonstrated by Griggs and Hartmann (1961), temperatures of 37.8 °C or greater during olive bloom reduce fruit set and fruit production.

The length of the flowering period was shorter in La Rioja than in Arizona, being approximately 15 and 20 days respectively. As has been shown, both the timing and length of flowering of olive cultivars can vary greatly between years, depending on climatic conditions within the same area (Rallo, 1997; Lavee *et al*., 2002). For example, the increase in olive production found in this trial is similar to that measured for the Manzanillo cultivar growing in Bet Shean, but greater than that recorded in Lahish, Israel (Lavee *et al*., 2002).

Even though supplemental pollination took place in La Rioja over a one day longer period than in Arizona, and on the last day the maximum–minimum temperature range in La Rioja was closer to the optimal for olive sexual reproduction, strong winds were present that day (Table 2). The occurrence of hot, dry winds during flowering has been associated with reduced fruit set. Winds or heat increase the natural abscission of olive inflorescences, flowers and fruit (Martin *et al*., 1994). On the days when the supplemental pollination trials took place in La Rioja and Arizona, maximum wind speeds were 37.0 and 33.3 km h^{-1}, respectively. Another factor that may have influenced the results is that the pollen was applied when the trees were in the full bloom stage in Arizona, and in the last third of the blooming period in La Rioja.

Overall, the Arizona branches had fewer fruits (both sexual and asexual) than those in La Rioja (Table 3). The difference could be associated with factors such as environmental conditions and agronomic practices (e.g. fertilization and irrigation).

In La Rioja, branches on the south side produced 63 and 25 % more olives than those on the north side of the trees for the treated and untreated rows respectively (Table 4). In Arizona, no difference in olive production between the east and west sides was found. Because olive tree metabolism is heavily influenced by sunlight, with shade resulting in reduced fruit production, a row running north and south has better overall light penetration than a row running east and west (Sibbett and Osgood, 1994; Childers *et al.*, 1995; Navarro and Parra, 1997). The differences in production between row sides in Arizona and La Rioja could be partially attributed to differences in row direction.

Another factor that could have influenced the differences in olive production found on the north and south sides in La Rioja is wind. Strong winds from the south and north are typical in the Arid Chaco ecosystem, and they blow all year long. However, the north winds in general are dry and warm, and these characteristics increase in the spring (Boletta, 1988), during the season when olives are in bloom. Detrimental effects of the hot, dry north winds on grapes and fruit trees in the Arid Chaco regions of La Rioja have been reported (Giunta and Giunta, 1977). In general, dry winds during the blossom period have been shown to inhibit growth, shorten the production season and affect fruit set by desiccating the stigmas in other tree species (Childers *et al.*, 1995; Núñez-Elisea and Crane, 2000).

The parthenocarpic fruit known as a shotberry occurs for reasons that have not been clearly explained, but there is a popular consensus that profuse numbers of shotberries generally occur when pollination is poor (Martin *et al.*, 1994; Cuevas *et al.*, 2001). The results of the Arizona trial are in agreement with this relationship (Table 3). In La Rioja, no relationship between sexual fruit and asexual fruit set variations was found, as evidenced by the lack of a significant ($p < 0.05$) difference in shotberry production between treatments. These results suggest that the general belief about the relationship between olives and shotberries may not be valid.

Compatibility test

The pollen compatibility that was found between Arbequina and Manzanillo cultivars is considered a significant finding. Since the Arbequina cultivar is widely distributed throughout the olive growing regions of Argentina, harvesting of pollen could be done readily, and the pollen used for supplemental application. This is not so for the Sevillano cultivar, since relatively few fields of this cultivar have been planted in Argentina.

The failure to detect a significant difference in olive production between branches pollinated with Arbequina and Sevillano pollen could have arisen because of the difference in pollen viability between cultivars. The Arbequina pollen had approximately twice the viability of the Sevillano pollen. Additional research is needed to establish definitively the Arbequina cultivar as being a good source of pollen for Manzanillo olives.

The Manzanillo trees that were cross-pollinated with Ascolano pollen showed no significant increase in olive production compared to the control. This is in agreement with other trials which have shown a high degree of incompatibility between Manzanillo and Ascolano cultivars (Cuevas *et al*., 2001).

CONCLUSIONS

This study has shown that supplemental pollination of Manzanillo olive trees using Sevillano pollen increases fruit yield under hot arid environments. Use of supplemental pollination as a general agronomic practice could provide growers with increased olive yields in the Sonoran Desert and Arid Chaco regions of North and South America, as well as in other hot arid regions of the world in which olives are, or might be, planted.

The cross-pollination trial showed that Manzanillo yields increase following supplemental pollination with Arbequina pollen. These results provide a new option for countries such as Argentina which have limited numbers of Sevillano trees, but where Arbequina is widely cultivated, since pollen required for supplemental application could be locally harvested.

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