PERFORMANCE CHARACTERISTICS OF

Lesquerella fendleri AS INFLUENCED BY PLANT DENSITY

by

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ABSTRACT

Lesquerella fendleri has been targeted for domestication to provide the U.S. chemical industry with a domestic source of hydroxy fatty acids. Field studies of density, harvest dates and shadehouse investigations of water stress were initiated to determine the response of seed and oil yields in _Lesquerella_.

Field thinned plants were grown at 250,000; 500,000; 750,000; 1,000,000; and their unthinned controls of 1,658,000 plants/ha in 1992-1993 and 1,500,000 plants/ha in 1993-94. Increasing density in 1992-93 resulted in reduction of vegetative growth, and a decline in harvest index through decreases in the number of branches and siliques/branch. Increasing density also reduced seed number/silique in the control and the 750,000 plants/ha treatments, without effecting other seed characteristics. Density increased taproot length and height in the 750,000 plants/ha treatments. Greatest seed yields were obtained at 750,000 and 1,000,000 plants/ha and the lowest in the extreme density treatments. Seeds produced in the lowest density also had lower oil content.

Second year data at final harvest, 264 days after sowing (DAS), did not show differences in seed and oil yields among treatments. However, developing seeds did show differences in oil yield, due to variations in timing of maximum oil

accumulation. The 750,000 plants/ha treatment reached peak oil deposition around 203 DAS, followed by 1,500,000 and the 500,000 plants/ha treatments at 229 DAS, and finally the 1,000,000 and 250,000 plants/ha treatments at 243 DAS. The earliest oil formed was devoid of auricolic acid in the 750,000 and 1,000,000 plants/ha treatments, and was dominated by stearic, oleic, linoleic, and linolenic acids. Later depositions were mostly lesquerolic acid. At normal harvest, 264 DAS, the 750,000 plants/ha treatment accumulated greater proportion of auricolic acid.

Early termination of irrigation at the beginning of flowering, and at one, two, and three weeks after flower initiation decreased height, taproot length and the number of branches/plant. Termination of irrigation during the first week of flowering reduced flowering and silique production. Water deficits reduced seed yield through abortion of siliques and declining seed weight. Irrigation through harvest did not demonstrate higher water use efficiency than termination of watering two weeks after flowering.

INTRODUCTION TO DISSERTATION

Between 120 to 180 million metric tons (MT) of oilseeds, corresponding to 38 to 60 million MT of oil and fats, are produced annually (Pryde and Doty, 1981; Jones, 1983; Salunkhe and Desai, 1986; Mackie, 1988; Hatje, 1989) from over 156 million hectares of the world's farmland (FAO, 1989). Oil-bearing crops include both annual species and perennial tree crops. Several annual plant species account for more than 50% of the world's oil output; these include soybean (Glycine max L.), sunflower (Helianthus annus L.), peanut (Arachis hypogaea L.), safflower (Carthamus tinctorius L.), rapeseed (Brassica napus L.), flaxseed (Linus usitalissimum L.), sesame (Sesame indicum L.), maize (Zea mays L.), and cotton (Gossypium spp.) (Doty, 1983; Jones, 1983; Lusas, 1983; Pryde, 1983).

Tree crops account for 19% of the world's oil production. Oil-bearing trees generally grow in tropical and sub-tropical climates, and take four to six years after planting before they become productive. Then they may produce crops or seeds for several decades, with peak yields around the twelfth year of plant growth (Doty, 1983). This group includes coconut (Cocos nucifera L.), oil palm (Elaeis guineensis L.), olive (Olea europaea L.), tung (Aleurites fordii L., A. montana L.), castor (Ricinus communis L.), stillingia (Sapium sebiferum L.), and oiticica (Licania rigida L.) (Pryde and Doty, 1981; Doty, 1983; Pryde, 1983).

Oilseeds have served several purposes throughout human history. They were used in ancient Egypt as medicinal and cosmetic products. More than 4,000 years ago, they often provided a source of fuel for lamps and soap-making (Pustovoit, 1973; Lusas, 1983; Smith, 1988; Roethli et al., 1991). Currently, they are used mostly as foods, raw materials for international trade, and in various industrial applications, at volumes corresponding to 12, 67, and 88%, respectively, of the world's total output (Pryde, 1979a,b; Pryde and Doty, 1981; Salunke and Desai, 1986). Oilseeds and their derivatives contribute 9 to 11% of the world agricultural trade (Ojola, 1979; Anon., 1989) with an export value of $18.4 billion (Alburo, 1989). Such trade provides foreign currency for internal development in technologically less advanced countries (Salunkhe and Desai, 1986), and contributes towards trade balance in developed nations (Pryde, 1979a; Ojola, 1979).

The U.S. oil market consumes approximately 6 to 8 million MT of vegetable oil and fat annually to meet both its edible and industrial needs (Pryde, 1979a; Pryde and Doty, 1981). Nearly 90% of this volume is supplied by domestically grown annual oil crops (Jones, 1983; Pryde, 1983). The major oil producing crops include flax, peanut, safflower, soybean, sunflower, and cottonseed.

Currently, soybean is the predominant oilseed in the U.S.

Its production has shown phenomenal growth since the crop was first introduced in the 1920s (Wolf and Cowan, 1975; Doty, 1983; Wolf, 1983). Between 1961 and 1981, soybean acreage increased from 11 to 27 million ha, and seed production rose sharply from 21 to 61 million MT. Total soybean production accounts for 86% of the oilseed harvest, 78% of oil processed, 83% of animal feed, and nearly all the edible protein in the U.S. Soybean exports, in the form of meal, oil, and seed, make up 24% of the world's output (Pryde and Doty, 1981; Pryde, 1983; Wolf, 1983), with an estimated value of $6.7 billion annually (Mackie, 1988).

Many factors have contributed to the predominance of soybean production during recent years, but the most important are the competitive pricing of oil (42 ¢/Kg) and meal $198/ton (Pryde and Doty, 1981; Pryde, 1983). The development of refining procedures has resulted in 5 to 6% greater recovery of the oil with the advent of the solvent extraction process as opposed to the former screw pressing process (Doty, 1983; Wolf, 1983). A net profit of $220/ha has provided a further economic incentive to growers (Pryde and Doty, 1981; Doty, 1983). Moreover, the plant's favorable agronomic characteristics of wide climatic adaptability in temperate zones (ranging from latitude 0° to more than 50°) have resulted in an improved yield in soybean (60%), relative to earlier cultivars (<u>Glycine soja</u> L.) (Hymowitz and Harlan, 1983). This is due to a combination of breeding and better cultural practices (Pryde and Doty, 1981; Knowles, 1983).

Sunflowers were the second fastest expanding oil crop in the U.S. Sunflower acreage expanded from 2000 ha in 1962 to nearly 2 million ha by 1980 (Zimmerman, 1981; Doty, 1983; Wolf, 1983). This phenomenal expansion is largely the result of the advent of the hybrid sunflower from Russia, whose oil content is 10 to 15% higher than unimproved varieties (Pustovoit, 1973; Zimmerman, 1981; Doty, 1983; Knowles, 1983), along with the strong European demand for sunflower to crush into oil and meal (85% of the U.S. sunflower export), and the high economic return of the crop with a net profit of $245 /ha (Doty, 1983; Zimmerman, 1981; Lusas, 1983; Wolf, 1983).

In recent years, there has been a decline in the acreage of soybeans by 8% (Fehr, 1989) and sunflowers by 34% (Fick, 1989) in the U.S. due to the leveling off of world demand, increases in quantities produced in competitive exporting countries (Brazil and Argentina), and to stepped-up efforts to increase domestic production by traditional importing countries, mainly members of the European Economic Community (E.E.C.) (Mielke, 1988; Smith, 1988). Flaxseed and safflower have also declined in production; their respective outputs have dropped more than 50% over the last decade due to a reduced demand for their oil in alkyd paints, varnishes, and oil cloth (Pryde, 1979b; Doty, 1983; Pryde,1983). Safflower growth faces limitations in terms of production areas which are confined to small, irrigated surfaces in California (dryland) and rainfed production in Minnesota, South and North Dakota, Montana, and Idaho. Such regional confinement has driven prices up to three times that of soybeans. Two forms of safflower exist: high linoleic and oleic, estimated at 80% and 20% of U.S. production, respectively. About half of the safflower harvest is exported to Japan, Taiwan, and Europe. There is a strong demand for high oleic safflower in the U.S. and Japan because of the boom in so-called Mediterranean diets and interest in monounsaturated oils. This trend will likely contribute to the expansion of safflower production (Smith, 1988). Cottonseed and peanut production, however, have remained almost constant due to competition from synthetic fibers for the former (Pryde, 1979a,b), and acreage control for the latter (Doty, 1983).

The United States is a major exporter of oilseed, controlling about 78 and 31% of soybean seed and oil export production, respectively, 74% of cottonseed, 5% of linseed, 27% of peanut, 85% of sunflower, and all of the safflower export production (Pryde, 1983; Wolf, 1983; Smith, 1988). In spite of important quantities of vegetable oil produced, the U.S. still imports about 10% of its vegetable oil, or approximately 785,000 MT, in order to meet specific requirements for lauric aid (coconut oil, palm kernel), palmitic acid (palm oil), long chain fatty acid or high erucic acid (rapeseed oil), 4-oxo-9, 11, 13 octadecatrienoic acid (oiticia oil), α-eleostearic acid (Tung oil) and ricinoleic acid (castor oil) demands (Pryde, 1979a,b; 1983; Lessman and Anderson, 1980; Roetheli et al., 1991).

Research efforts have been initiated to find alternate domestic sources for most imported oils (Thompson et al., 1992). These efforts have had varying degrees of success. Progress in domestication of *Cuphea* spp., a lauric acid source, was limited by excessive seed shattering (Smith, 1988; Thompson et al., 1992). Commercial production of crambe (*Crambe abyssinica* L.), a source of high erucic acid, was uneconomical for its low and inconsistent seed yields and lack of genetic variability (Lessman and Anderson, 1980; Smith, 1988; Thompson et al., 1992). Incomplete exploration of the industrial potential of meadowfoam (*Limnanthes alba* L.) has resulted in hindrances to its commercial development (Jolliff, 1981; Smith, 1988; Thompson et al., 1992).

In contrast to other imported oilseeds, castor was grown in the U.S. between 1950 and the early 1970s, but a combination of low economic returns (from the absence of price support systems), difficulty in handling the crop, workers' allergic reactions, and toxic meals, resulted in abandoning the crop's production (Smith, 1988; Thompson et al., 1989; Roetheli et al., 1991). Castor oil contains ricinoleic acid and its derivative, sebatic acid. These are classified as critical materials by the U.S. Department of Defense (Smith, 1979).

Castor seed contains between 25 to 50% oil. Ricinoleic acid is the major hydroxy fatty acid representing 80 to 87% of this oil. The chemical structure of ricinoleic acid includes hydroxyl groups, double bonds, and carboxyl groups. Castor seed oil is used industrially in the U.S. for the manufacture of different products, principally resins, waxes, plastics, nylon, corrosion inhibitors, cosmetics, coatings, pharmaceuticals and in grease formulation for high performance military and industrial equipment (USDA, 1991, 1992). Castor is essentially imported from Brazil and India and its annual use in the U.S. varies between 30 to 60 thousand MT with a value of 30 to 35 million dollars (Thompson et al., 1989; Carlson et al., 1990; Roetheli et al., 1991; USDA, 1992).

Because of the importance of castor oil to U.S. industry, the existence of a domestic source of hydroxy fatty acid is of paramount importance. The seed of Lesquerella spp. produces an oil which contains three related hydroxy fatty acids: lesquerolic, densipolic and auricolic, fatty acids similar to those of castor. Division of Lesquerella fatty acids, into the three groups is based on the predominance of one hydroxy form, which usually occurs to the exclusion of the other two acids (Smith et al., 1962; Smith, 1979). Of the three, the chemical structure of lesquerolic acid, which includes the hydroxyl group, double bonds and the carboxyl groups, is the most closely related to and may serve as a substitute for ricinoleic acid from castor oil (Smith, 1979).

Because of their special chemical attributes, the hydroxy fatty acids of Lesquerella can be used in a wide range of products, including resins, waxes, nylons, corrosion inhibitors, cosmetics, coatings, pharmaceuticals and in grease formulations for high performance military and industrial equipment (USDA, 1991). Furthermore, the seed meals of Lesquerella are found to have comparable quality and composition to other cruciferous meals from crambe and rapeseed. Lesquerella meal is relatively high in lysine containing 6.64 g/16g nitrogen (Miller et.al., 1962; Carlson et al., 1990) and is thought to have good potential as a protein supplement for feed grains. Glucosinates are found to be present, as with other cruciferous seed meals, but none are found to give rise to goitrogenic substances (thioxazolidanes) (Daxenblichler et al., 1962; Miller et al., 1962; Thompson and Dierig, 1988; Carlson et al., 1990; USDA, 1991; Thompson et al., 1992). Lesquerella fendleri, a prime candidate for domestication, produces seeds containing 11 to 39% oil. The hydroxy fatty acid content (lesquerolic), ranges from 50 to 75% (Thompson and Dierig, 1988).

Commercial production of Lesquerella requires the development of efficient production and marketing systems. Although agronomic studies on Lesquerella production techniques were launched in 1985 (Thompson and Dierig, 1988; USDA, 1991; Thompson, et al., 1992), there is little or no information on cultural practices that affect seed yield, oil content and quality. Pertinent cultural practices involve the determination of optimum plant density per unit area, appropriate harvest time for maximum seed and oil yields, and an assessment of water stress during the reproductive phase.

The result of a Lesquerella density trial conducted at The University of Arizona, Maricopa Agricultural Center showed a yield increase paralleling the plant population, despite an observed decline in harvest index and vegetative weight. The yield differences between 100,000 and 1,100,000 plants/ha treatments were 26%. Parameters measured were yield/ha, height, width, and individual plant harvest index (Thompson et al., 1989).

The existing information on Lesquerella does not provide a thorough understanding of how an increase in population density affects plant growth and yield components. This research was undertaken to answer basic questions related to the effect of plant density on agronomic performance of Lesquerella grown in the field under irrigation. An additional attempt was made to assess the effect of moisture deficit during the reproductive stage on seed yield of

Lesquerella grown in the shade house.

This dissertation presents the summary of findings of three main studies, appended as separate manuscripts to be submitted for publication. The first manuscript (APPENDIX A) reports the results of the overall growth and yield component parameters of Lesquerella fendleri grown at five plant populations: 250,000; 500,000; 750,000; 1,000,000; and 1,658,000 plants/ha. The purpose of this study was to determine the optimum planting density for seed and oil yield and to estimate the effect of population on Lesquerella's yield components. The hypothesis tested was that there were no treatment differences for seed and oil yields of Lesquerella harvested at full maturity. The underlying rationale was that sparser stands develop larger canopies which intercept radiation more efficiently than partially developed canopies from denser populations, and therefore, yield components will negate yield differences between the two populations. In addition, the sparse nature of Lesquerella in the wild in Arizona (David A. Dierig, pers. comm.) may favor lower stands for maximum yield over denser stands.

The second manuscript (APPENDIX B) discusses seed oil content and compositional changes as functions of time of harvest. It also compares the second year yield results of Lesquerella grown at five plant populations: 250,000; 500,000; 750,000; 1,000,000; and 1,500,000 plants/ha. The purpose was to monitor the deposition of oil in developing Lesquerella seeds, in order to attempt to predict the proper harvest time for maximum economic return under different plant densities. The hypotheses were that no treatment differences for oil content and composition in developing seeds, but, that mature seeds have higher oil content than developing seeds. The rationale is partially based on castor seed, whose hydroxy fatty acid (ricinoleic acid) reaches maximum oil deposition at maturity (Weiss, 1971).

The third manuscript (APPENDIX C) deals with the effect of moisture deficit during the reproductive stage on seed yields. The purpose was to determine the impact of early irrigation termination, during the reproductive phase, on flowering, silique and seed formation. It was hypothesized that early irrigation termination would not result in a decrease in seed output of stressed compared to non-stressed plants. The rationale was that water deficit causes an increase in flower and silique abortions, thus reducing the number of seeds (sinks) as observed in soybean (Taylor et al., 1982) and simultaneously increasing the individual seed weight. Fewer heavier seeds produced from water stressed plants will compensate for the greater number of lighter seeds from the control.

Biology and natural history of Lesquerella

Lesquerella is a crucifer with chromosomes numbers ranging from 2n = 10 through 2n = 20. It is highly self-incompatible allowing a high degree of cross pollination among genetically related species. The occurrence of polyploidy is very limited, and until recently, Lesquerella rectipes was the only known polyploid species (Rollins, 1955; Rollins and Shaw, 1973; Rollins and Solbrig, 1973; Rollins and Rudenberg, 1979). The genus, with more than 70 species, is chiefly native to the arid parts of western North America from east-central Mexico to Alberta and Saskatchewan. A few representative species are also found in limited areas of South America, Alabama, Kentucky, and Tennessee (Miller et al., 1962; Mikolajcz et al., 1962). The greatest concentration of species is in the Rocky Mountains of the southern U.S., northern Mexico, and the intermountain basin region of the western U.S.(Thompson et al., 1992).

The natural habitat of Lesquerella varies in altitude, ranging from 600 to 1800 m and in annual precipitation from 25 to 45 cm. The most common soils in its range are well drained, alkaline and sandy, or soil of a calcareous nature, often rich in phosphorous and deficient in nitrogen. Lesquerella may also be found in disturbed areas including roadsides, abandoned fields, or open habitats in grasslands where they frequently form extensive, dense and almost pure stands. Exceptionally, certain species, such as Lesquerella gracilis, grow in black clay soils of north and south-central

Oklahoma (Barclay et al., 1962; Gentry and Barclay, 1962).

Lesquerella contains annual, biennial, and perennial species (Barclay et al., 1962). Annuals represent about two-thirds of the known species (Mikolajcz et al., 1962; Miller et al., 1962). Lesquerella plants are described as spring annuals or perennials because many species start growth in the fall, begin to flower in early March, develop rapidly at the onset of spring and may continue seeding into early summer. Plants may also show erect or decumbent growth, and possess several to many stems developing into long, peduncled racemes with yellow or white flowers.

Flowering proceeds as the raceme elongates. The length of flowering depends on the amount of available moisture. In seasons of below normal rainfall, flowering may last a week or two. When rainfall is adequate, flowering continues for three or more weeks, or, with intermittent rainfall, may occur in distinct flushes. Flowers produced along the stem develop into spherical siliques or capsules containing numerous flattened seeds (Barclay et al., 1962; Gentry and Barclay, 1962; USDA, 1991). A mature Lesquerella fendleri capsule contains 10 to 26 small seeds. There are commonly 10 to 15 capsules in each raceme. A well developed plant has 40 to 50 racemes and exceptionally large individual plants may bear 400 racemes. A heavily seeded plant yields about 14g of seed per year (Gentry and Barclay, 1962).

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APPENDIX A. PERFORMANCE CHARACTERISTICS OF *Lesquerella fendleri* AS INFLUENCED BY PLANT DENSITY

PERFORMANCE CHARACTERISTICS OF *Lesquerella fendleri* AS INFLUENCED BY PLANT DENSITY

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PERFORMANCE CHARACTERISTICS OF *Lesquerella fendleri* AS INFLUENCED BY PLANT DENSITY

ABSTRACT

Recommended planting density for optimum seed and oil yields/unit area of *Lesquerella fendleri* has not been determined for successful commercial production in Arizona. The effects of plant density on growth, yield, and yield components of *Lesquerella fendleri* were studied in central Arizona at plant populations of 250,000; 500,000; 750,000; 1,000,000 and controls of 1,658,000 plants/ha in 1992-93 and 1,500,000 plants/ha in 1993-94. Increasing density resulted in a significant decrease in plant height, width, and biomass, while causing an increase in taproot length in populations up to 750,000 plants/ha. There were no effects on seed weight, volume and test weight, however, density significantly reduced the number of branches/plant above 500,000 plants/ha and the number of seeds/silique for the 750,000 and 1,658,000 plants/ha treatments. Seed yield and harvest index/plant were significantly reduced with increasing density but yield/ha increased with density up to 1,000,000 plants/ha. At 1,658,000 plants/ha, shattering was excessive and resulted in significant loss of seed. The greatest seed yield/ha were obtained at the 750,000 plants/ha and the 1,000,000 plants/ha densities. The oil content did not vary significantly from

500,000 to 1,658,000 plants/ha, but the 1,000,000 plant/ha treatment produced seeds with significantly higher oil content than the 250,000 plants/ha. Differences in oil yield/ha reflected differences in seed yield/ha. Harvest in 1993-94 did not show significant differences in seed and oil yields among density treatments.

Key words : *Lesquerella fendleri*, plant density, yield components, oil content.

INTRODUCTION

Lesquerella is found mainly in the arid parts of western North America, where more than 70 species have been identified in the wild (Miklojczak et al., 1962; Miller et al., 1962). Currently, the major supply of vegetable hydroxy fatty acids used in the U.S. chemical industry is imported castor from Brazil and India (Smith, 1988; Roetheli et al., 1991). Castor seed oil is used industrially for the manufacture of different products, principally resins, waxes, plastics, nylons, corrosion inhibitors, cosmetics, coatings, pharmaceuticals, and grease formulations for high performance military and industrial equipment (USDA, 1991, 1992). There has been interest in domesticating *Lesquerella* to provide the U.S. with a domestic source of hydroxy fatty acids. *Lesquerella fendleri* is considered the prime candidate for domestication because of its superior agronomic potential (Thompson, 1985; Thompson and Dierig, 1988; USDA, 1992), and the close resemblance of its major fatty acid (lesquerolic acid) to the ricinoleic acid found in castor (Smith, 1979).

Despite recent research efforts on Lesquerella, there is no recommendation for optimum planting density (Thompson et al., 1989). However, response of growth and yield to plant density are well documented in many major crops. Degenhardt and Kondra (1981), Morrisson et al. (1990b), and Van Deynze et al. (1992) reported that low plant densities in rapeseed (Brassica napus L.) resulted in increase production of biomass and seeds/plants because of reduced competition among individual plants, with its associated benefit of improved canopy radiation interception. The factors responsible for increase seed yield under low planting densities are positive responses of yield components, such as, increase in fruiting branches, fruiting units, and seed number and weight in castorbean (Ricinus communis L.) (Kittock and Williams, (1970), in faba bean (Vicia faba L.) (Graf and Rowland, 1987), in soybean (Glycine max L.) (Blumenthal et al., 1988), and in rapeseed (Morrisson et al., 1990a).

Under high population densities at least one, if not several key elements of yield components may impair seed yield potential, and therefore, result in low yields. Holt and Zentner (1985),in sunflower (Helianthus annus L.), Graf and Rowland (1987) in faba bean, and Gravois and Helms (1992) in rice (Oryza sativa L.), indicated that the reduction in harvest index is one of the most common features associated with high density. Low harvest index is caused by either small or poorly filled seeds, or a combination of both. Other studies with sunflower (Gubbels and Dedio, 1986) referred to delay in flowering resulting from crowding (heavy seeding rate) while Van Deynze et al.(1992) considered lodging a contributing factor. On the other hand, however, the generation of more fruiting units/area, observable in high planting densities provide the means to increase seed yield as opposed to fewer fruiting units in lower densities in snap bean (Phaseolus vulgaris L.) (Wahab et al., 1986) and in rice (Gravois and Helms, 1992). Increase seed yield with increased population, in cowpea (Vigna unguiculata L.) is obtainable only when plants have a high harvest index (Kwapata and Hall, 1990).

There is little information available regarding the response of Lesquerella fendleri to planting density. The initial study carried out on this plant by Thompson et al. (1989) involved six population treatments: 100,000; 131,000; 200,000; 222,000; 344,000 ; and 1,100,000 plants/ha. Their data showed that the low density treatment produced 26% less seed yield than the densest population, although the harvest index and the vegetative weight/plant of the latter were, respectively, 12 and 86% lower than that of the lowest population. The sources of variation for seed yield and growth differences in this study were not identified.

The objective of this study was to examine the effects of plant density on seed yield, yield components and growth parameters of Lesquerella fendleri grown under rainfed conditions with supplemental irrigations.

MATERIALS AND METHODS

This research was conducted from 7 October 1992 through 23 June 1993 and 30 September 1993 through 20 June 1994 at The University of Arizona, Maricopa Agricultural Center on Casa Grande reclaimed sandy loam (fine loam, mixed, hyperthermic typic natrargid). The seeds sown during the 1992-93 growing season were collected from the 1991 harvest of Lesquerella fendleri, and those sown during 1993-94 were collected from the 1993 harvest (June 1993). Sowing rates were 15.7 Kg (1.6 million seeds/Kg) in both of the growing years. Prior to sowing, ammonium phosphate (16-20-0) was broadcast at a rate of 112 Kg/ha.

The experimental plots occupied an area of 400 m^2 (10 x 40 m) chosen in the middle of a large field to minimize the effects of borders. The stand of fully established Lesquerella 1992-93 was estimated at 1,658,000 plants/ha on 17 December 1992 and that of 1993-94 was estimated at 1,500,000 plants/ha on 11 January 1994. The population estimates were determined by averaging plant counts of the eight unthinned replicated plots ($8x1m^2$). A randomized block design with eight replications and five population treatments was used to evaluate growth and yield performance of Lesquerella fendleri. The treatments were 250,000; 500,000; 750,000 and 1,000,000 plants/ha; with the unthinned control of 1,658,000 plants/ha. Desired plant populations were obtained on 17 December 1992 for the 1992-93 growing season and 11 January 1994 for the 1993-94 growing season by thinning plants in 25 grids (20 x 20 cm) delineated within a square meter to 1, 2, 3, or 4 plants/grid for 250,000; 500,000; 750,000; and 1,000,000 plants/ha, respectively. The controls were not thinned and had about 6 to 7 plants for every 20 x 20 cm grid. Repeated thinnings were performed to remove later emerging seedlings in the four population treatments.

During growth, plants received 22 cm of winter rain in 1992-93 and 23 cm in 1993-94, and eight supplemental irrigations each year averaging 3-4 cm each. The total water applied was estimated at 50 cm. Weeds were controlled by hand pulling.

Growth Measurements

A total of 80 tagged plants in 1992-93 (2 plants/plot) were used to determine the sequential development of plant height and width. The measurements (cm) were made at 134, 149, and 163 days after sowing (DAS) for plant width. Height continued to increase past 163 DAS, and additional measurements were taken at 177 and 192 DAS. Dry matter accumulations were determined periodically until plants reached their maximum growth in height and width. At each sampling period two plants (shoots and roots) were selected randomly from each plot, and oven dried to constant weight at 60° C. Sampling periods were 134, 149, and 192 DAS. At the last sampling (192 DAS), taproots (length) were measured when they were considered fully developed based on cessation of plant growth. Taproots were carefully dug out of well moisted soil to maintain their integrity using a small trawl. Individual plant biomass was determined by weighing sundried and ground level clipped plants due to difficulties in recovering the taproot system because of the soil dryness. A total of 40 x 40 cm duplicate quadrats were harvested as sampling units for each plot for biomass, yields and yield component determinations in 1992-93. Seed yield estimates were obtained in 1993-94 from the harvest of the entire plots.

Phenology

Flower production was recorded in 1992-93 over time by counting the number of plants/plot with inflorescences at 134, 149, 163, 220, and 233 DAS. Senescence was estimated by counting the number of plants/plot with drying aerial organs (leaves and stems). Counting was done at 192, 205, 220, and 233 DAS. Stages of seed development were estimated by changes in silique color as either green or brown, and was observed at

192, 205, 220, and 233 DAS.

Yield Components

The number of branches produced were counted periodically during growth at 134, 149, 163, and 233 DAS in 1992-93. Silique formation was recorded at 177, 192, 233, and 260 DAS. At harvest, 23 June 1993, the number of aborted siliques/branch were counted, seed yield/unit area, harvest index and seed characteristics (1000-seed weight, volume, test weight, and number) were determined.

Oil Analysis

For each plot, about 2 to 4 g of seed were collected and used for oil analysis in 1992-93 and in 1993-94 harvests. Oil content in 1992-93 was determined at the National Center for Agricultural Utilization Research (NCAUR), Peoria, Illinois. Seed oil contents from duplicated samples were measured using a Bruker PC120 pulsed NMR analyzer. The seed oil content in 1993-94 was determined at The University of Arizona, Bioresources Research Facility, Tucson, Arizona. Total oil content was obtained by computing the relative weight of different fatty acids in the seed. Fatty acid contents were determined by trans-esterification of the oil and gas chromatography (GC) analysis using a RESTEK 15m 0.25mm ID, 0.25µ film thickness STABILWAX column of the resulting esters as described by Thompson et al. (1994).

Statistical Analysis

The variables of interest in this study before harvest were analyzed using SAS (SAS Institute, 1988). Post- harvest data, mainly plant biomass, seed characteristics, seed yield, and oil content were analyzed with CoStat (Cohort software, Berkeley, CA). In both analyses, $P \leq 0.05$ was used to define statistical significance and means were compared using Duncan's Multiple Range Test and the standard error of the means.

RESULTS AND DISCUSSION

Density had major effects on Lesquerella's growth characteristics. Final height differed significantly among treatments between the 750,000 plants/ha (41 cm) and the control (unthinned) (31 cm), however, no significant differences existed between the control and the remaining treatments (Table 1). Initial plant height measured at 134 DAS showed significant differences among treatments (Figs. 1a-5a). The 250,000, 500,000, and 750,000 plants/ha treatments were 2 cm taller than the 1,000,000 plants/ha (12 cm vs 10 cm) and 6 cm taller than the control (12 cm vs 6 cm). This advantage was maintained throughout the growth period. The 500,000 plants/ha treatment reached their maximum height at 177 DAS while elongation continued until 192 DAS for the other treatments, particularly the 750,000 plants/ha treatment.

These results demonstrated that increasing plant density resulted in a minor decrease in plant height, except for the 750,000 plants/ha treatment. In general, increasing density restricted height early in growth as much as 17% for the 1,000,000 plants/ha treatment and 50% in the control as a result of competitive forces for available space. This is comparable to the observations reported in rapseed (Degenhardt and Kondra, 1981; Morrison et al., 1990b) and in peanut (Arachis hypogea L.) (Roa et al.,1989). The data herein reported are not consistent with the findings of Thompson et al. (1989) who observed a linear increase in height with density up to 900,000 plants /ha in Lesquerella fendleri. Additionally, these results differ considerably from the linear and quadratic responses often noted in sunflower (Gubbels and Dedio, 1986) and in soybean (Blumenthal et al., 1988). The exceptional height for the 750,000 plants/ha treatment may be partially explained by the ability of these plants to explore more moisture in deep soil (18 cm) between two consecutive irrigations (14 d) than the shallow taproot system (9 cm) of the control (Table 1).

The effect of increasing density was consistent with respect to plant width. As plant population increased, width decreased significantly (Table 1). The lowest density treatment had the widest plants (35 cm) while the control produced the smallest plants (13 cm). These width differences were apparent at early growth (134 DAS) (data not shown). The restricted width growth observed at early and at the end of growth demonstrated the role of competitive forces for available space with increasing density as noted in rapeseed (Dengenhardt and Kondra, 1981; Morrisson et al., 1990b), and in peanut (Rao et al., 1989).

Taproot length measured at cessation of height and width growth (192 DAS), displayed significant differences among treatments (Table 1). There was an increase in taproot length with increasing density up to 750,000 plants/ha, thereafter a sharp decrease followed with additional plants. The 500,000 and 750,000 plants/ha treatments had the longest root systems (14 cm, 18 cm) while the control produced the shortest (9 cm). The increase in taproot length with density or row spacing has been reported in soybeans (Mason et al., 1982; Blumenthal et al., 1988) and in peanut (Rao et al., 1989). It has been suggested that root proliferation in denser populations provides the means by which plants extract additional water during periods of stress. In this study, the signs of wilting were the least visible in the 750,000 plants/ha treatment. The proliferation of the root system in this population density may have played a significant role in extracting water at depth between two successive waterings of the plants.

Flower production was low (<1%) at 134 DAS and not evenly distributed (no flowers were present in 750,000 and 1,000,000 plants/ha) (Table 2). However, at 149 DAS, all treatments had produced flowers, but with considerable differences in percentage of plants with flowers. The control contained nearly 50% of plants with inflorescences while the 1,000,000 plants/ha had only 19%. All plants were flowering in all treatments at 163 DAS. Later flowering (flush = open flowers after most of the siliques turned brown or mature) did not differ among treatments at 220 and 233 DAS (data not shown). The flowering pattern observed in this study was different from reported cases in the literature for sunflower (Gubbels and Dedio, 1986) where increasing density resulted in delay in flowering.

The yield components of Lesquerella include the number of branches/plant, the number of siliques/branch, the number of seeds/silique, and the seed weight. The component most reduced by increasing plant density was the final number of branches/plant. There were significant decreases in the number of branches with increasing population (Table 3). Reductions in number of branches averaged 31, 35, and 51% for 750,000, 1,000,000 and 1,658,000 plants/ha, respectively, compared to the number of branches in the 250,000 plants/ha treatment. Reduction trends in the number of branches with respect to increasing planting density have been observed in rapeseed (Degenhardt and Kondra, 1981) and in soybean (Weil and Ohlrogge, 1976; Blumenthal et al., 1988).

Density had no significant effect on the number of siliques/branch, (45-54 siliques/branch) (Figs. 1b-5b) nor on the number of siliques harvested/branch (17-22 siliques/branch) (Table 3). These results, however, demonstrated two important phenomena. First, plants in plots of various densities, behaved similarly in both their pattern of production (silique/branch) and amount of silique losses (53-68%) before and during harvest. Second, there was no compensation for silique production to offset the loss of component branches resulting from increased density. Such a lack of compensation explained the seed yield decrease/plant as a result of reduced production of siliques/plant (number of branches x number siliques/branch). These results confirm early observation by Graf and Rowland (1987) in faba beans and Morrison et al. (1990a) in rapeseed.

Seed characteristics, primarily 1000-seed weight, test weight and volume were not affected by increasing density (Table 4). These results are in agreement with those of Kittock and Williams (1970) in castorbean, Degenhardt and Kondra (1981) and Van Deynze et al. (1992) in rapeseed, Blumenthal et al. (1988) in soybean, Thompson et al. (1989) in Lesquerella, and Beech and Leach (1989) in chickpea. However, increasing density significantly reduced the number of seeds/silique in the 750,000 plants/ha treatment and the control. The probable causes of reduction in the number of seeds for the former may have resulted from intense competition for metabolites, from day 177 through 192 DAS, between vegetative and reproductive sinks. During this time interval, plants elongated by 5 cm while producing 45% of their siliques; thus exceeding the 250,000, 500,000 and the 1,000,000 plants/ha treatments in both vegetative growth (height) by 4 to 5 cm and in reproductive load (silique) by 20 to 25% (Figs. 1ab-4ab). Graf and Roland (1987) found that vegetative apices of faba beans are greater physiological sinks than reproductive structures and because of this, competition between these two organs results in reduced fruit set. Another study reported a reduction in seed number/pod when vegetative and reproductive organs simultaneously require photoassimilates for growth in soybeans (Egli et al., 1985).

The reduction in seed number/silique in the control could not be caused by vegetative growth during reproduction since this growth was negligible, only 1 cm (Fig. 5ab) which was similar to growth observed in the 250,000, 500,000 and the 1,000,000 plants/ha treatments (Figs. 1, 2 and 4). However, the reductions could be explained partially by the effects of shading of the low canopy, causing poor canopy interception of the photosynthetically active radiation as observed in rapeseed (Addo-Quaye et al., 1986) and in soybeans (Mason et al., 1982; Taylor et al., 1982). The strong intraspecific competition due to crowding and finally, the shallow taproot system of plants may have prevented the exploration of moisture or nutrients at deep soil profiles.

Vegetative and seed yield/plant at harvest decreased significantly with increasing plant density (Table 5), as a result primarily of declining number of branches (Tables 3). The 250,000 plants/ha treatment produced 5 times more vegetative material (23.7g vs 5.3g) and 8 times more seed yield/plant (3.7g vs 0.46g) than did the control. As a consequence, the harvest index declined from 0.18 for the 250,000 plants/ha treatment to 0.08 in the control (Table 5) confirming several earlier observations including studies of rapeseed (Dehenhardt and Kondra, 1981) soybeans (Blumenthal et al., 1988) chickpeas (Beech and Leach, 1989) and Lesquerella (Thompson et al., 1989).

Seed yield/ha increased with density up to 1,000,000 plants/ha and thereafter declined sharply (Table 6). Extremely low and high densities resulted in low seed yield/ha as a consequence of reduced number of branches/unit area for the former, and excessive shattering or lower seed number/silique for the latter (Tables 3 and 4).

Oil content was significantly lower in the 250,000 plants/ha compared to the 1,000,000 plants/ha treatment (Table 6). The reason for maximal accumulation of oil in the 1,000,000 plant/ha treatment is unclear. However, the seed characteristics (volume, 1000-seed weight, and test weight) of this treatment are numerically superior to those of other treatments and may have contributed to the slight increase in oil. Oil yield followed the same trend as seed oil content, increasing with density up to 1,000,000 plants/ha and then decreasing sharply (Table 6). Extremely low and high densities resulted in low oil yield/ha as a consequence of low seed yield/ha. Production of oil was maximal at the 750,000 and 1,000,000 plants/ha treatments reflecting the seed yields of these treatments.

The variables weight of seeds, oil, and seed yields in 1993-94 are presented in Table 7. There were no significant differences among treatments for these variables. This study confirmed earlier results for the variable seed weight (Thompson et al., 1989). However, the similarity of seed yield and oil content for all the treatments contradicted the 1992-93 studies that found a reduced yield for the 250,000 and the control (1,658,000 plants/ha treatments), and a lower oil content for the 250,000 plants/ha density relative to the 1,000,000 plants/ha treatment. The increase in oil for the 250,000 plants/ha treatment may be partially explained by the high temperatures during seedfill in May and June 1994 during which the average daily temperature recorded at the Maricopa Experimental Station (about 700 m from the experimental site) were respectively 36.6° C and 42.9° C compared to 36.6°C and 40° C for the same months in 1993. Such a rise in temperature by 2.9° C in June 1994 may have accelerated the maturation of seeds as noted in wheat (Triticum eastivum L.) (Weigand and Cuellar, 1981; Hunt et al., 1991) that would otherwise have not developed and would have been lost at harvest. The effect of incorporating late maturing seeds can increase the oil content of this treatment. Thompson and Kleiman (1988) reported an increase up to 0.5% in oil of Cuphea when late maturing seeds were incorporated with timely harvested seeds.

High temperatures (2.9°C above the daily temperature of June 1993), were also believed to contribute to seed yield increase augmenting the proportion of seeded siliques through acceleration of the seedfill. Under cooler temperatures, seedfill progresses slowly and may never be completed before harvest for some siliques, therefore, causing more potential seed losses. The seed increase in the control (1,500,000 plants/ha) were caused by a probable reduction in shattering which appeared to be limited in 1994 in comparison to the shattering observed before and during the harvest of 1993. During this study, the number of windy days was very low, substantially reducing seed losses through shattering.

CONCLUSION

Increasing density resulted in a significant decrease in Lesquerella's plant height, width, and dry biomass. However, density increased taproot length up to 750,000 plants/ha. Maximum root length was associated with extreme height possibly due to deeper soil water and nutrient explorations.

In general, density affected growth parameters early in the development and growth differences observed early among treatments do not vary considerably at the time of harvest. Therefore, treatment effects for growth characters can be assessed or predicted in the beginning of plant development.

Seed yield and harvest index/plant were severely reduced with increasing density as a result, primarily, of reduction in number of branches. Seed volume, density, and test weight were not affected by density, although seed number/silique, significantly decreased in the 750,000 plants/ha and control treatments. The decrease of 33% for the control was probably caused by low canopy shading, poor radiation interception and severe competition among plants, while a possible explanation for the 750,000 plants/ha decline (23%) may have resulted from the vegetative and reproductive competition between day 177 and 192 DAS. Seed yield/ha increased with density, as well as, shattering percentage (1992-93). Shattering was enhanced by early maturity and contributed considerably to yield losses in extremely high density treatments. Oil content was not affected by increasing density, but greater oil deposition required a maximum of 500,000 plants/ha (1993-94). Production of oil/ha paralleled seed yield/ha because of the small variation in oil percentage among treatments.

Table 1. Mean ($\pm$SE) final height, width, and taproot length/plant of *Lesquerella fendleri* grown at five different plant populations in 1992-93.[a]

Plants /ha	Plant height (cm)	Plant width (cm)	Taproot length (cm)
250,000	37 $\pm$ 1.89 ab	35 $\pm$ 1.75 a	11.0 $\pm$ 12.17 bc
500,000	36 $\pm$ 0.87 ab	31 $\pm$ 1.63 ab	14.0 $\pm$ 1.16 ab
750,000	41 $\pm$ 4.00 a	28 $\pm$ 1.93 bc	18.0 $\pm$ 0.72 a
1,000,000	35 $\pm$ 3.00 ab	25 $\pm$ 1.30 c	13.0 $\pm$ 1.91 bc
1,658,000	31 $\pm$ 0.50 b	13 $\pm$ 1.20 d	9.0 $\pm$ 0.73 c

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

Table 2. Mean (±SE) percentage of plants with flowers of Lesquerella fendleri from day 134 (February 17) through day 163 (March 18, 1993) after sowing, grown at five plant populations.[a]

Plants/ha	Day 134 (2-17) %	Day 149 (3-4) %	Day 163 (3-18) %
250,000	0.375 ± 0.18 a	31.50 ± 6.70 b	100 ± 0.0 a
500,000	.375 ± 0.18 a	28.50 ± 5.00 b	100 ± 0.0 a
750,000	- -	29.75 ± 2.00 b	100 ± 0.0 a
1,000,000	- -	18.75 ± 3.00 c	100 ± 0.0 a
1,658,000	0.375 ± 0.18 a	48.12 ± 7.18 a	100 ± 0.0 a

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.
- - no flower present at the time of count.

Table 3. Mean ($\pm$SE) number of branches and siliques/plant of *Lesquerella fendleri* grown at five plant populations at the time of harvest (on June 23, 1993).[a]

Plants/ha	Number of branches	Number siliques/branch
250,000	43 $\pm$ 3.83 a	19 $\pm$ 1.34 a
500,000	34 $\pm$ 5.12 ab	22 $\pm$ 2.59 a
750,000	29 $\pm$ 3.39 bc	19 $\pm$ 1.63 a
1,000,000	28 $\pm$ 3.87 bc	18 $\pm$ 1.99 a
1,658,000	21 $\pm$ 2.67 c	17 $\pm$ 1.11 a

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

Table 4. Mean (±SE) number seeds/silique and seed volume/1000-seed/weight and test weight of *Lesquerella fendleri* grown at five plant population in 1992-93.

Plants/ha	Seeds/silique	Range	Seed volume (ml)	Weight (g/1000seeds)	Test weight (g)
250,000	18±1.50a	2-36	0.85±0.08a	0.69±0.00a	0.67±0.00a
500,000	16±1.60a	4-28	0.96±0.07a	0.72±0.00a	0.66±0.00a
750,000	14±1.30b	4-28	0.79±0.07a	0.65±0.01a	0.64±0.01a
1,000,000	16±1.00a	4-26	1.02±0.12a	0.71±0.03a	0.70±0.03a
1,658,000	12±1.10b	4-26	0.88±0.07a	0.65±0.01a	0.65±0.01a

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

Table 5. Mean (±SE) vegetative weight, seed yield and harvest index/plant of *Lesquerella fendleri* grown at five plant populations in 1992-93.[a]

Plant/ha	Vegetative weight (g)	Seed weight/plant (g)	Harvest index[b]
250,000	23.7±3.28a	3.70±0.67a	0.18±0.06a
500,000	19.8±2.02a	2.00±0.34b	0.10±0.00b
750,000	18.8±2.37a	2.00±0.22b	0.10±0.00b
1,000,000	15.0±1.71b	1.50±0.13b	0.10±0.00b
1,658,000	5.3±0.42c	0.46±0.05c	0.08±0.00c

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

[b] Harvest index = plant seed weight/plant aboveground weight.

Table 6. Mean (±SE) seed and oil yields/hectare and percentage of oil at the 1992-93 harvest of *Lesquerella fendleri* grown at five plant populations.[a]

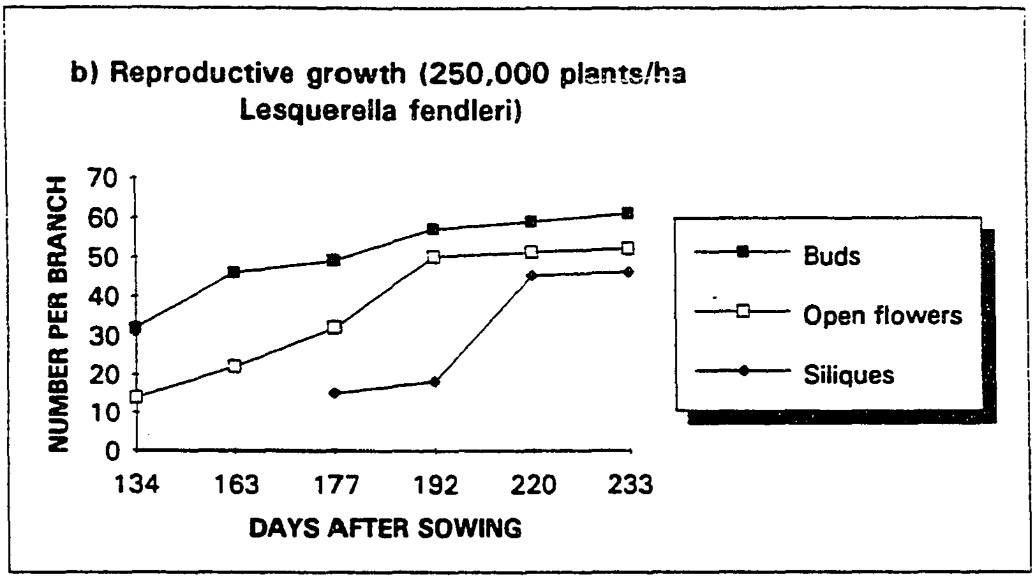
Plants/ha	Seed yield/ha (kg)	Oil content %	Oil yield /ha (kg)
250,000	992.9 ± 189.7 c	22.5 ± 0.40 b	226.3 ± 42.90 c
500,000	1039.5 ± 174.4 bc	23.0 ± 0.31 ab	239.5 ± 45.80 bc
750,000	1442.3 ± 100.4 ab	23.2 ± 0.67 ab	337.2 ± 29.20 ab
1,000,000	1539 ± 134.5 a	24.2 ± 0.70 a	377.3 ± 43.50 a
1,658,000	830.4 ± 41.7 c	22.9 ± 0.31 ab	190.6 ± 10.40 c

[a] Mean within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

Table 7. Mean (±SE) seed weight (1000 seeds), seed yield/hectare and percentage of oil at the 1993-94 harvest of Lesquerella fendleri grown at five plant populations.[a]

Plants/ha	Weight of 1000 seeds (g)	Seed Yield (Kg/ha)	Oil (%)	Oil Yield (Kg/ha)
250,000	0.64a	1164.00±79.5a	20.10±0.81a	213.00±18.09
500,000	0.62a	1248.00±100a	23.70±1.57a	261.00±28.97a
750,000	0.64a	1458.00±80.2a	20.20±1.47a	265.20±24.50a
1,000,000	0.64a	1400.00±49.5a	23.90±1.39a	311.20±26.54a
1,5.00,000	0.65a	1452.00±106a	21.40±1.81a	286.00±23.45a

[a] Means within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.



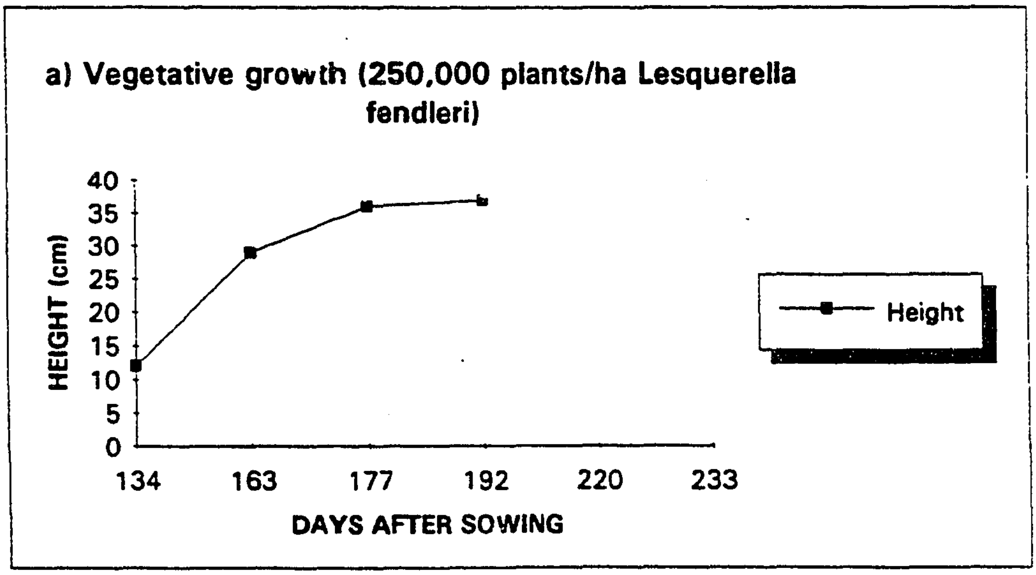


Figure 1. Growth of Lesquerella fendleri at 250,000 plants/ha in 1992-93 from day 177 (April 1) through day 233 (May 27, 1993).

a) Vegetative growth: elongation in height between day 177 (April 1) and day 192 April 15, 1993) during silique formation.

b) Reproductive growth: cumulative production of buds, open flowers, and siliques/branch (siliques smaller in size than those containing seeds were not counted).

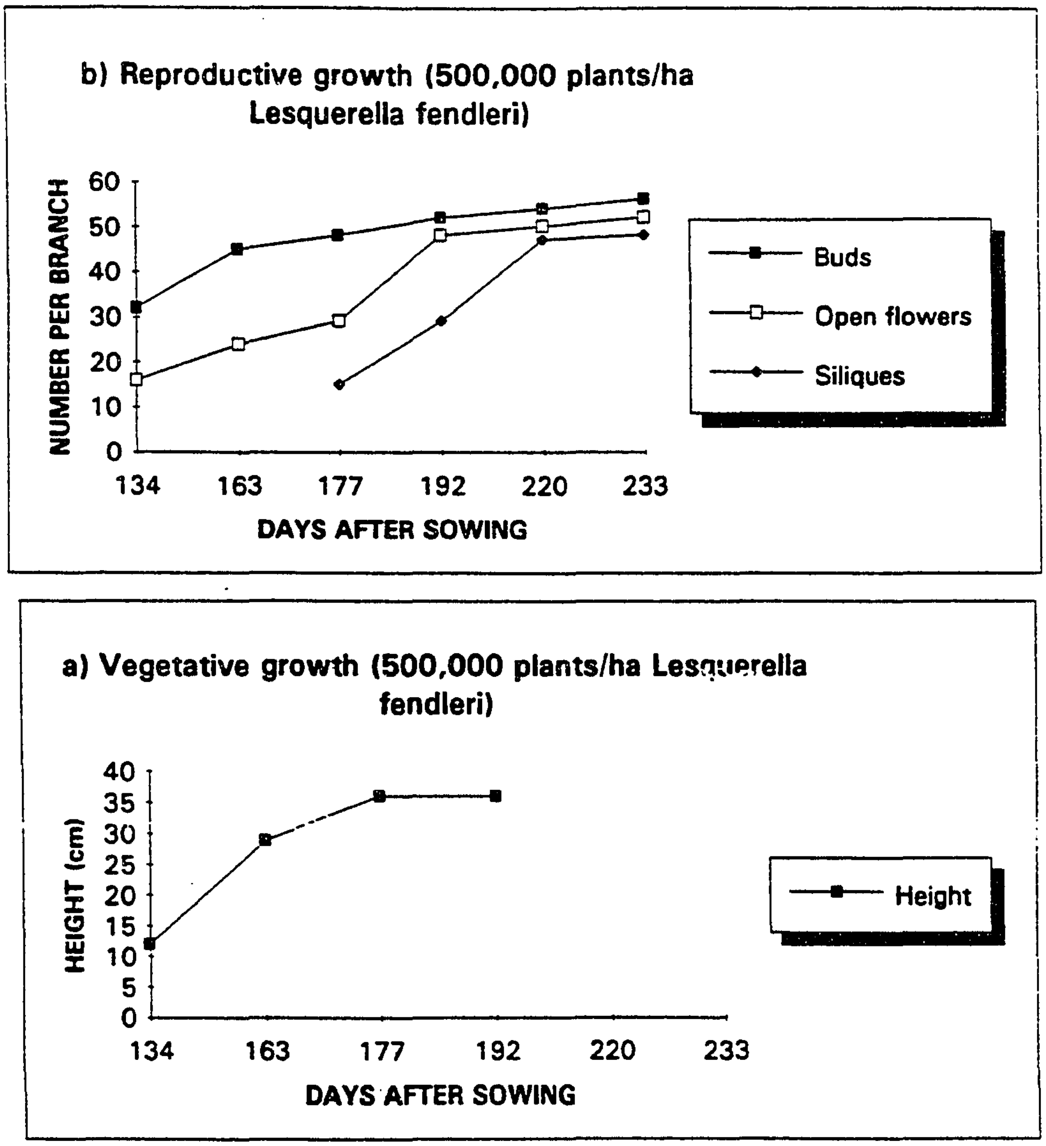
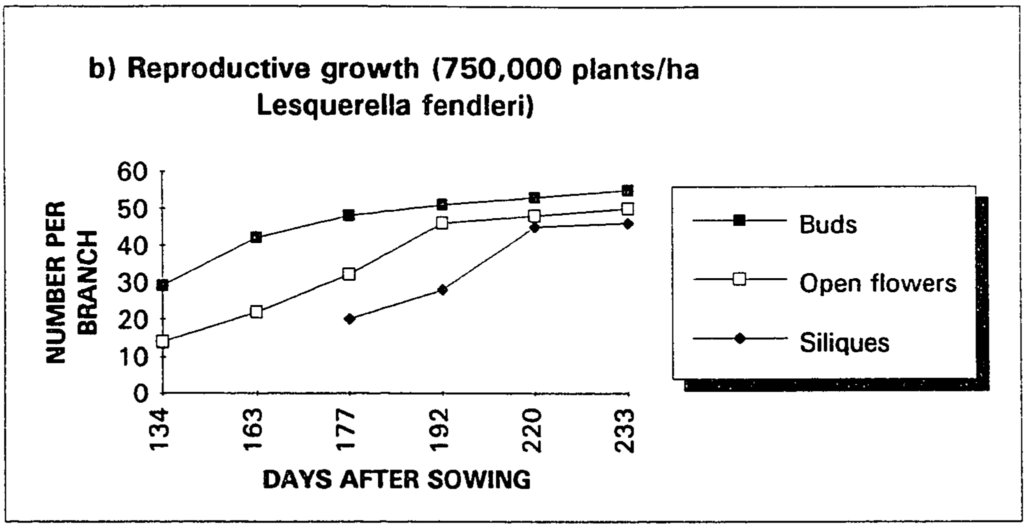


Figure 2. Growth of Lesquerella fendleri at 500,000 plants/ha in 1992-93 from day 177 (April 1) through day 233 (May 27, 1993).
a) Vegetative growth: elongation in height between day 177 (April 1) and day 192 April 15, 1993) during silique formation.
b) Reproductive growth: cumulative production of buds, open flowers, and siliques/branch (siliques smaller in size than those containing seeds were not counted).



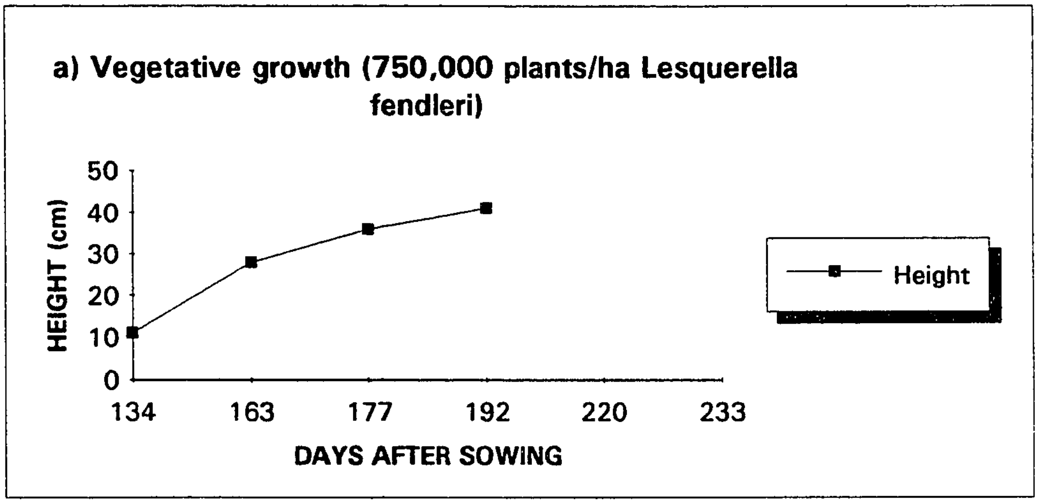
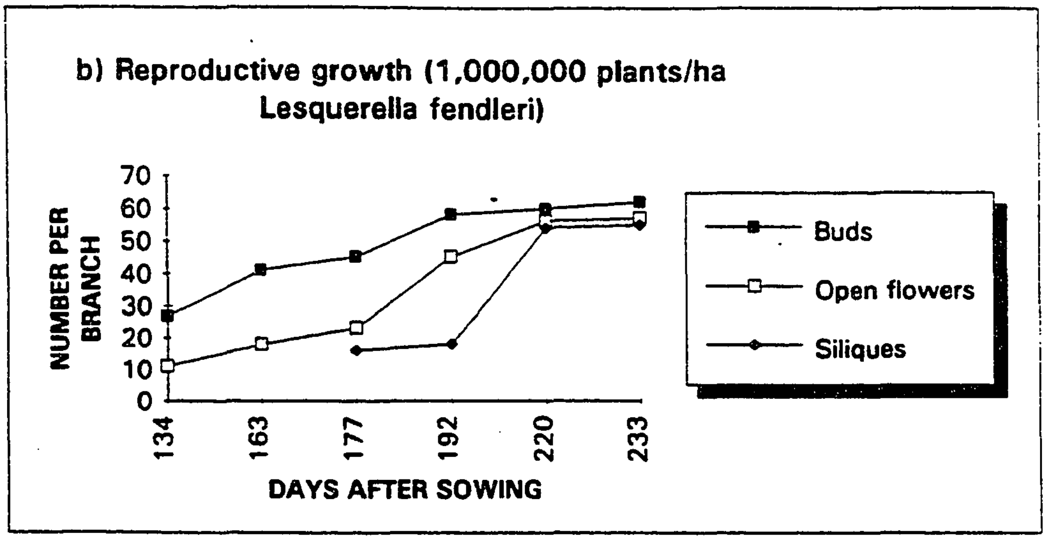


Figure 3. Growth of Lesquerella fendleri at 750,000 plants/ha in 1992-93 from day 177 (April 1) through day 233 (May 27, 1993).
a) Vegetative growth: elongation in height between day 177 (April 1) and day 192 April 15, 1993) during silique formation.
b) Reproductive growth: cumulative production of buds, open flowers, and siliques/branch (siliques smaller in size than those containing seeds were not counted).



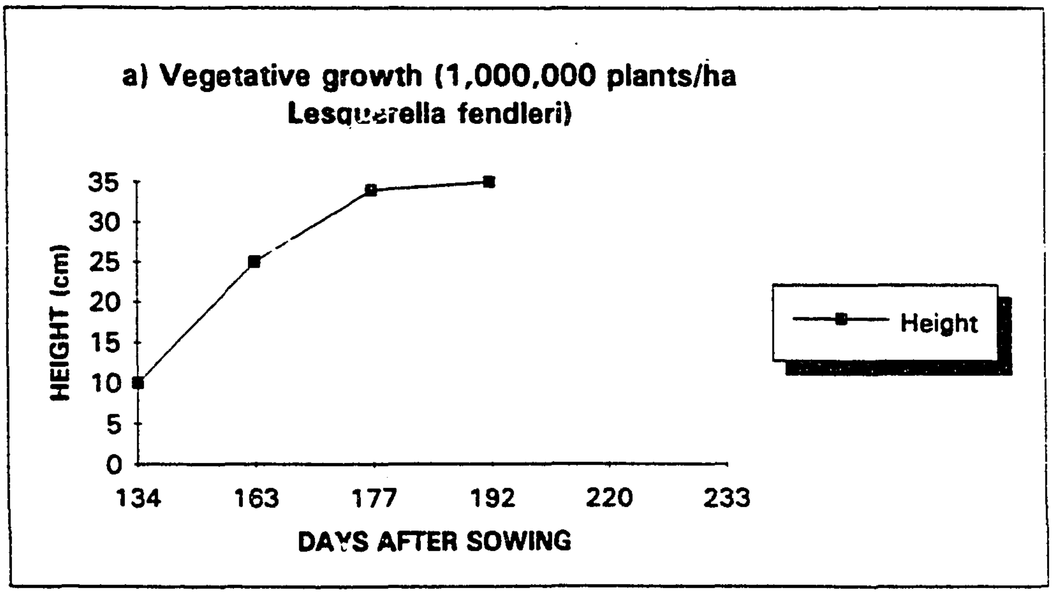
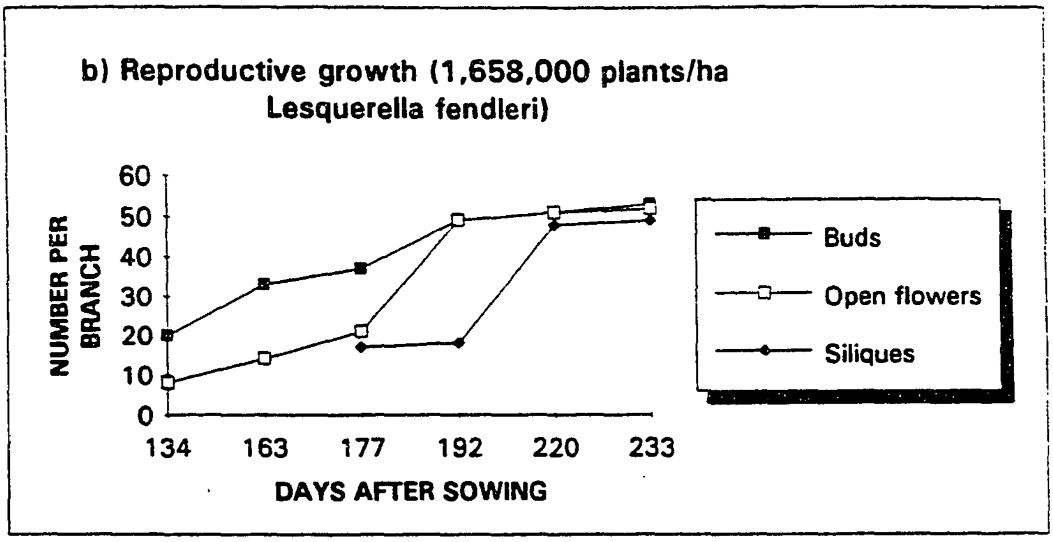


Figure 4. Growth of <u>Lesquerella fendleri</u> at 1,000,000 plants/ha in 1992-93 from day 177 (April 1) through day 233 (May 27, 1993).
a) Vegetative growth: elongation in height between day 177 (April 1) and day 192 April 15, 1993) during silique formation.
b) Reproductive growth: cumulative production of buds, open flowers, and siliques/branch (siliques smaller in size than those containing seeds were not counted).



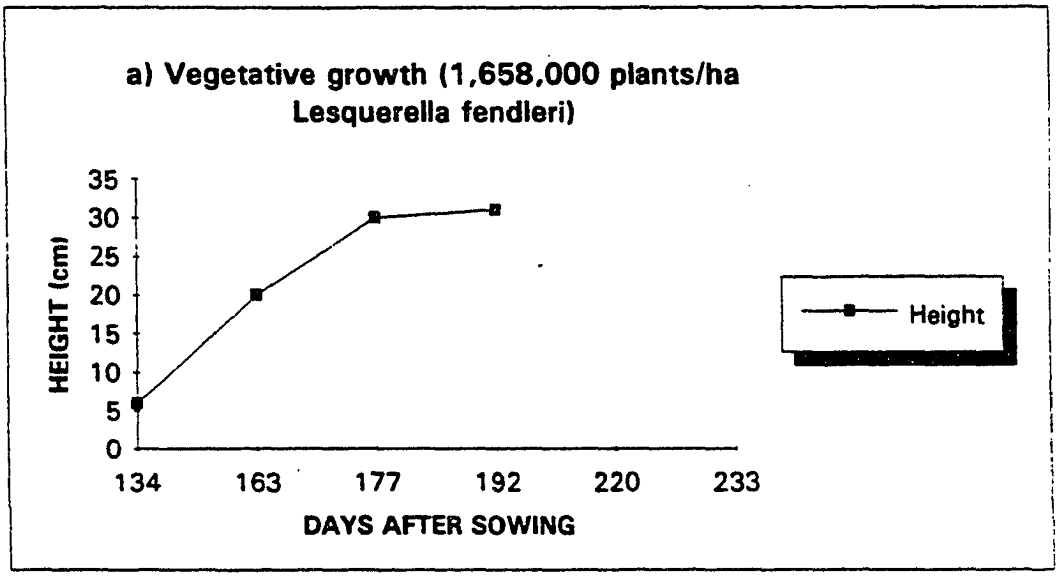


Figure 5. Growth of Lesquerella fendleri at 1,658,000 plants/ha in 1992-93 from day 177 (April 1) through day 233 (May 27, 1993).
a) Vegetative growth: elongation in height between day 177 (April 1) and day 192 April 15, 1993) during silique formation.
b) Reproductive growth: cumulative production of buds, open flowers, and siliques/branch (siliques smaller in size than those containing seeds were not counted).

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APPENDIX B. EFFECTS OF HARVESTING DATES ON OIL YIELD AND COMPOSITION IN *Lesquerella fendleri*

EFFECTS OF HARVESTING DATES ON OIL YIELD AND COMPOSITION IN *Lesquerella fendleri*

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EFFECTS OF HARVESTING DATES ON OIL YIELD AND COMPOSITION OF *Lesquerella fendleri*

ABSTRACT

Limitation of yield losses occurring during harvest of *Lesquerella fendleri*, as results of seed shattering and reduced oil content of excessively desiccated seed may be accomplished through appropriate choice of harvest dates. However, there are no reported information of such dates to maximize economic returns at any planting density of *Lesquerella*. This research was undertaken to study the effects of harvest dates and plant populations on oil yield and composition in *Lesquerella fendleri*. Mechanically seeded field plots of *Lesquerella fendleri* were thinned at 103 days after sowing (DAS) to density treatments of 250,000; 500,000; 750,000; 1,000,000; and unthinned control of 1,500,000 plants/ha. These plants were grown in 1993-94 at The University of Arizona, Maricopa Agricultural Center in central Arizona, and were harvested at 203, 229, 243, and 264 DAS. Eight fatty acids, contributing 87-96% of mature seed oil, were investigated. These included, palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), lesquerolic (C20:1-OH), and auricolic (C20:2-OH). Generally, seed harvested at 203 DAS had lower concentrations of palmitoleic, stearic, oleic, lesqueriolic, and auricolic acids and lower oil contents than

those harvested at 229, 243, and 264 DAS. At 203 DAS the 750,000 plants/ha treatment produced the highest oil yield at early harvest, although this oil, and that from the 1,000,000 plants/ha treatment, were devoid of auricolic acid. During this period, the major contributing fatty acids to oil content were oleic, linoleic, linolenic, and lesquerolic. Harvest at 229 DAS resulted in an increase in oil content for all treatments except 750,000 plants/ha. Lesquerolic acid was the dominant contributor of this oil for the unthinned control. At 243 DAS, higher oil contents were observed in the 250,000, 750,000, and 1,000,000 plants/ha densities, with lesquerolic acid again the dominant fatty acid. At final harvest (264 DAS) lesquerolic acid content was virtually the same among density treatments.

INTRODUCTION

The recovery at harvest of high yield and good quality seed is emphasized in agricultural settings to maximize economic returns. Improper decisions at harvest time can limit both high yield and good quality seed production. For example, field studies of delayed harvests have shown severe yield reduction, ranging from 16 to 93%, as a consequence of seed shattering by wind, rain and combining in meadofoam (Limanthes alba L.) (Calhoun and Crane, 1978) and in sesame (Sesame indicum L.) (Salunkhe and Desai, 1986). The extent of shattering is influenced by seed size (Smith, 1988), and by crop species (Calhoun and Crane, 1978; Thompson and Kleiman, 1988).

Similarly, premature harvest of developing seed have demonstrated considerable seed and oil depressions as a result of poor filling and low oil depositions (Dillman, 1928; Mazzani and Allievi, 1966; Rubel et al., 1972; Dornbos and McDonald, 1986; Dahmer et al., 1991). These depressions result from insufficient dry matter and oil accumulations during the weeks following anthesis (Dillman, 1928; Mazzani and Allievi, 1966; Hill and Knowles, 1968; Dahmer et al., 1991).

Detailed biochemical investigations of developing seed have indicated that oil synthesis begins four to nine days after flowering in flax (Linum usitatisium L.)(Dillman, 12928; Hill and Knowles, 1968) and maximum oil accumulation occurs twenty-eight days after anthesis followed by a slight decline in oil content at seed maturity in safflower (Carthamus tinctorius L.), sesame, and soybean (Glycine max L.) (Leininger and Urie, 1963; Mazzani and Allievi, 1966; Seiler, 1986; Dahmer et al., 1991). A longer oil accumulation period has also been reported in castorbean (Ricinus communis L.), soybean (cv. Acme and Harosoy 63), and rapeseed (Brassica napus L.) (Cavin, 1963; Rubel et al., 1972; Norton and Harris, 1975). During seed development fatty acid composition changes considerably with maturity Rubel et al., 1972; Norton and

Harris, 1975; Dornbos and McDonald, 1986; Dahmer et al., 1991) or with temperatures (Cavin, 1965; Harris et al., 1978; Seiler, 1986).

Attempts to relate maximum oil accumulation and seed moistures to determine appropriate harvest time has proven to be of very little practical significance, for moisture percentages are often high to allow mechanical harvest (Dillman, 1928; Rubel et al., 1972; Dedio, 1985; Dornbos and McDonald, 1986) and safe storage of seed (Salunkhe and Desai, 1986).

The relationship between density and oil content in several crops has been studied extensively, but the results have not been consistent. Findings such as those of Kittock and Williams (1970) in castorbean, Morrisson et al. (1990) and Van Deynze et al. (1992) in rapeseed report no observable effects. While Hoag et al. (1968) in safflower and Gubbels and Dedio (1986) in sunflower (Helianthus annus L.) showed a positive effect of density on seed oil content. In a recent study, it was observed that oil content of Lesquerella fendleri was higher in the density of 1,000,000 plants/ha compared to oil yield at 250,000 plants/ha (Appendix A). In its late growth stage, a typical Lesquerella plant bears mature (brown) and immature (green) siliques, along with young flowers (Gentry and Barclay, 1962). This varying degree of maturity imposed delayed mechanical harvest with its concomitant severe seed shattering and desiccation of seeds.

Bulk sampling of seed with different degrees of maturity has shown differences in palmitic acid content in sunflower (George et al., 1988), but not in oil content in Cuphea spp. (Thompson and Kleiman, 1988). There is no reported information on the effect of different harvest dates on the oil content and composition of developing seeds in Lesquerella fendleri. The objective of this study was to determine the effect of different harvest dates and plant populations on oil content and composition of developing Lesquerella fendleri seed in an attempt to identify an optimum harvest date for good seed and oil production.

MATERIALS AND METHODS

This research was conducted from 30 September 1993 through 20 June 1994 at The University of Arizona, Maricopa Agricultural Center on Casa Grande reclaimed sandy loam (fine loam, mixed, hyperthermic typic natrargid). The seeds were sown at a rate of 15.7 Kg/ha (1.6 million seeds/Kg) and were collected from the 1993 harvest (June 1993) of Lesquerella fendleri on a level field. Prior to sowing, ammonium phosphate (16-20-0) was broadcast at a rate of 112 Kg/ha.

The experimental plots occupied an area of 400 m^2 (10 x 40 m) chosen in the middle of a large field to minimize the effects of borders. The stand of fully established Lesquerella was estimated at 1,500,000 plants/ha on 11 January

1994 from average counts of individual plants in eight unthinned replicated plots (8 x 1 m^2). A randomized complete block design with eight replications and five population treatments was used to study the effect of harvest dates on oil yield and composition of _Lesquerella_ seed. The treatments were: 250,000; 500,000; 750,000; and 1,000,000 plants/ha; with a control of 1,500,000 plants/ha. Desired plant populations were obtained on 11 January 1994 by thinnings of 25 grids (20 x 20 cm) delineated within a square meter (m^2) to 1, 2, 3, or 4 plants/grid, representing populations of 250,000; 500,000; 750,000; and 1,000,000 plants/ha, respectively. The control was not thinned and had approximately 6 plants/grid. Repeated thinnings were performed to remove later emerged seedlings in the four population treatments. All weeds were hand pulled.

During growth, plants received 23 cm of winter rains in 1993-94 and 8 supplemental irrigation averaging 3-4 cm each. Total water applied was estimated at 50 cm .

Patterns of flower and silique formation were recorded to compare seed maturation sequences among treatments. The recording of these factors was taken from 155 days after sowing (DAS) through 187 DAS. The _Lesquerella_ seed utilized for oil and fatty acid analyses were harvested at 203, 229, 243, and 264 DAS. The last harvest coincided with seed maturity for mechanical harvest, when all siliques were brown and dry, while the two earliest harvests were carried out when the siliques were immature, green, and seeds were poorly developed and had high water content. Seed samples at the 243 DAS harvest were mostly mature with less than 10% of the seed classified as green and immature. The drying of seed prior to oil and fatty acid analyses was carried out in a greenhouse over two consecutive days, where day and night temperatures averaged 37^{0}C, and 23^{0}C, respectively.

Total oil content of sampled seed was obtained by determining the relative weight of palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), lesquerolic (C20:1-OH), and auricolic (C20:2-OH) fatty acids. Fatty acid composition was determined by trans-esterification of the oil (Thompson et al., 1994) and gas chromatography (GC) analysis using a RESTEK 15 m 0.25 mm ID, 0.25 µ film thickness STABILWAX column. Fatty acid methyl ester standards (Sigma Chemical Co., St. Louis, MO) were used to check peak retention times of the C16:0; C16:1; C18:0; C18:1; C18:2; C18:3; C20:1-OH; C20:2-OH fatty acids, based on known composition of previously harvested seeds. The variables of interest of this study were analyzed as a split-plot design with harvest dates as the main plot factors, and density as sub-plot factors, using the SAS package (SAS Institute, Raleigh NC, 1988).

RESULTS AND DISCUSSION

Seed moisture of the four selected harvest dates are shown in Table 1. There were no significant differences among the various treatments at each harvest date. Early harvest (203 DAS) coincided with high seed moisture (80-83%) that subsequently dropped to it lowest level (7%) at maturity (264 DAS). Observations of individual treatments at 203 DAS harvest clearly showed marked differences in oil content and composition (Table 2). The 750,000 plants/ha had the highest oil content (30.4%) while the 500,000 and 1,500,000 plants/ha treatments produced the lowest oil content (less than 6% oil) (Table 2) at comparable seed moisture levels (80-83%) (Table 1). The low oil content of the two latter treatments, resulted from the presence of a minimal amount of all fatty acids but specially in C20:1-OH that was one-third to one-fourth of the value found in the other treatments. The 750,000 and 1,000,000 plants/ha treatments were devoid of C20:2-OH. The absence of C20:2-OH in the oil of the 750,000 plants/ha density did not affect its observed oil yield (30.4%) as a consequence primarily of a substantial increase of two to six-fold of the C18:1, C18:2, and C18:3, and the C20:1-OH.

The biochemical significance of two treatments which had altered fatty acid composition in C20:2-OH (absence) but differed in oil yield (30.4% vs 13.2%) indicates either differences in seed age or rate of oil synthesis. It may furthermore suggest an inhibition in the C20:2-OH synthetic pathway early and at the time of maximum oil formation. Such inhibition possibly increased the amount of C20:1-OH in the 750,000 plants/ha treatment. Dahmer et al. (1991) reported an increase in monounsaturated lipids (oleic) at the time of polyunsaturated lipids (linoleic and linolenic) decline during seed development in soybeans. The decline in the level of polyunsaturated lipids during seed development in planta (soybeans) has been attributed to decrease activity of oleoyl desaturase (Stymme and Appleqvist, 1980). The total disappearance of the C20:2-OH with a concomitant rise in the C20:1-OH content of Lesquerella fendleri (750,000 plants/ha) may illustrate the biochemical events reported in Table 2.

The high variability in oil at 203 DAS, strengthens the suggestion that seed age or timing of oil deposition caused differences among treatments. Seed from the 500,000 and 1,500,000 plants/ha treatments were evidently the youngest by their low oil content (5.5%) and composition in storage fatty acids (C20:1-OH and C20:2-OH), representing only 17.8-42.8% of the amount accumulated in the other treatments (Table 2). Lesquerella closely resembles Crambe (Crambe abyssinica L.) and rapeseed in that they deposit the major storage lipids (lesquerolic and erucic acids) early in seed formation (Gurr et al., 1972; Norton and Harris, 1975). However, lesquerolic acid appears not to drop drastically during seed development in a comparable manner as rapeseed, underlining the fundamental biochemical differences between these two species (Norton and Harris, 1975).

A chronological classification of the seeds harvested at 203 DAS could logically be put in sequential order starting with the youngest being 500,000 plants/ha, followed closely by the control, then the 250,000 plants/ha, the 1,000,000 plants/ha, and finally the 750,000 plants/ha densities. Although significant differences were not detected for the silique numbers, there were quantitatively more siliques formed in the 750,000 plants/ha density at 162 DAS than any other treatments. During this period, the silique numbers observed for the treatments of 1,500,000 and 500,000 plants/ha, respectively, were 0 and $9/m^2$. The control matured quicker than the 250,000 plants/ha density, possibly under the competitive forces of density or simply this treatment invested greater resources toward reproductive structures at 203 DAS.

Percentage of fatty acids of different seed oils is shown in Table 3. Differences in oil yields and in C16:1 and C18:0 (Table 2) did not correspond to compositional variation (Table 3). However, the difference in C18:3 contents (Table 2) corresponded to a 9-15% increase in the composition of this fatty acid in the 750,000 plants/ha density compared to the composition observed in the other treatments (Table 3). Total oil content (29.4%) was higher for the control compared to the

250,000, 750,000, and 1,000,000 plants/ha treatments at the 229 DAS harvest (Table 4). There was an increasing trend in oil accumulation for all treatments, except for the 750,000 plants/ha density which declined from 30% to 24% (Tables 2 and 4). The C16:0 of the 1,000,000 plants/ha treatment, was the only fatty acid whose content declined between 203 and 229 DAS, by 35% (Tables 2 and 4). The decline in total oil for the 750,000 plants/ha treatment was caused principally by lesser proportions of the C18:1, the C18:2, the C18:3, and to a lesser extent the C16:0 fatty acids (Tables 3 and 5). These lower proportions coincided with the rises in the levels of the C20:1-OH fatty acids, the C16:1, the C18:0, and the C20:2-OH, but these additions were insufficient to compensate for the above losses.

There were no differences in the composition of the fatty acids at the 229 DAS harvest among treatments (Table 5). In all treatments C20:1-OH was the dominant fatty acid accounting for 51 to 53% of the oil.

The difference in the composition of oil at 203 DAS (Table 3) and at 229 DAS (Table 5) harvests poses an interesting question regarding the effect of environment. It has long been known that temperatures can alter fatty acid composition in rapeseed, sunflower, safflower, flax, and castorbean (Canvin, 1965; Harris et al.,1978; Jenny et al., 1984; ; Seiler, 1986) and this alteration is detectable within

6 hours after exposure of the oil synthesizing tissues to temperature changes (Slack and Rougham, 1978). In this present study, average maximum and minimum temperatures for the month of April were 30.9°C and 10.4°C, respectively, while the corresponding values for May were 35°C and 14.4°C. The likelihood of compositional changes of oil are greater for May than April based on known effects of temperatures (Cavin, 1965; Harris et al, 1978; Jenny et al., 1984).

The oil yield for the 750,000 plants/ha treatment (30.4%) demonstrated otherwise (Table 2). The discrepancy between the assumption and the observed data may be partially explained by the higher day temperature of 38.9°C the day before harvest, which could have altered the observed composition by increasing the proportion of the C18:3 two fold (27%) relative to the average composition of 13% in the other treatments. The absence of similar effects in the other treatments suggests that temperature was not solely responsible for this change, but also factors associated with seed development. Dedio (1985) pointed out that maximum oil accumulation occurs in sunflower a week before major fatty acids reach their greatest concentration. The trend in Lesquerella was similar to this reported observation. It is therefore possible to speculate that the 750,000 plants/ha treatment was at physiological maturity at the time of harvest at 203 DAS.

Harvest at 243 DAS, with seed moisture of 18-19% (Table 1), resulted in higher oil contents for the 250,000, 750,000 and 1,000,000 plants/ha treatments (approximately 26%) (Table 6). However, the 500,000 and 1,500,000 plants/ha treatments showed decreases from 29% at 229 DAS (Table 4) to 22% at 243 DAS (Table 6). The differences in oil, which ranged from 3.6% in the 500,000 plants/ha treatment to 7.5% in the 1,500,000 plants/ha treatment, were associated mostly with a drop in the level of the C20:1-OH and C18:1 compared to the harvest at 229 DAS. Conversely, oil increases were caused by rises in the amount of C20:1-OH (16-24%)along with the C18 compounds and C20:2-OH (Tables 4 and 6). The fatty acid composition was similar for all treatments (Table 7).

Differences in oil content were not detected at final harvest, (264 DAS)or maturity harvest (Table 8) when seed moisture dropped to its lowest level (7%) (Table 1). There was a trend toward lower oil contents for all treatments, except for the 500,000 plants/ha density which had a slight oil increase (2%) as result of the rise in the levels of the C20:1-OH. Decline in oil content of seed from the four other treatments were caused primarily by a fall in the amount of the C20:1-OH. The fatty acid composition (Table 9) exhibited few differences among treatments. Significant differences were noted only for higher C20:2-OH at the 750,000 plants/ha density. The increase in oil content at maturity (264 DAS) for the 500,000 plants/ha treatment could be explained partially by the harvest of late maturing seeds in the seed samples. This treatment has been known to produce large vegetative organs (Appendix A) delaying seed maturation. The maximum temperature ranges from March to June 1994 were very high (26.7°C to 42.9° C) and accelerated the maturation of many seed that would otherwise have been lost. The contribution of such seed in the samples could cause a rise in content as observed in this study.

CONCLUSION

Seed moisture of Lesquerella fendleri harvested at 203,229,243, and 264 DAS dropped considerably (83% to 7%) during the course of study. Density had no effect on seed moisture changes. Harvest at 203 DAS altered seed oil composition with increases in the proportions (48% to 65%) of the C18 compounds (oleic, linoleic, and linolenic) and absence of auricolic acid in the 750,000 and 1,000,000 plants/ha treatments. Lesquerolic acid dominated the fatty acid composition (51-53%) of the seed oil at 229 DAS and at latter harvest (243 and 264 DAS). Density did not reduce final oil yield, but caused major variation in timing of maximum oil deposition. It also caused an increase in the composition of linolenic (203 DAS) and auricolic acids (264 DAS) in the 750,000 plants/ha treatment. High seed moisture (46-83%) presents major constraints in optimizing production in early oil yielding treatments such as the 750,000 plants/ha treatment at 203 DAS and the 500,000 and 1,500,000 plants/ha treatments at 229 DAS. Late harvest (264 DAS) at a time of excessive seed dehydration (7%) resulted in oil decline ranging from 8% in the 500,000 and 1,000,000 plants/ha treatments to more than 20% in the extreme densities (250,000 and 1,500,000 plants/ha treatments). It would appear that harvest at 243 DAS is the most appropriate for all density treatments because of favorable combination of seed moisture (17-19%) and good oil yield (22-26%). Under the current growing conditions, the 1,000,000 plants/ha treatment may offer the best yield, possibly because their maximum oil accumulation occurs close to maturity and experiences minor oil decline (8%) at maturity (264 DAS). However, under a limited spring moisture environment the early oil forming treatments (500,000, 750,000, and 1,500,000 plants/ha treatments) may provide drought avoidance and limit severe production losses.

Table 1. Moisture content of <u>Lesquerella fendleri</u> seed grown at five plant populations and four harvest dates.[a]

	Harvest dates			
	Day 203 (04/21/94)	Day 229 (05/17/94)	Day 243 (06/01/94)	Day 264[b] (06/21/94)
Plants/ha	% Moisture			
250,000	83.0 ± 3.51a	53.1 ± 5.54a	19.0 ± 1.0a	7.0 ± 0.0a
500,000	82.4 ± 4.25a	50.5 ± 4.38a	19.2 ± 0.9a	7.0 ± 0.0a
750,000	81.8 ± 5.60a	48.1 ± 5.62a	18.5 ± 1.2a	7.0 ± 0.0a
1,000,000	80.5 ± 3.72a	51.4 ± 5.78a	18.8 ± 2.4a	7.0 ± 0.0a
1,500,000	80.0 ± 3.34a	46.0 ± 3.95a	17.5 ± 2.8a	7.0 ± 0.0a

[a] Means within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

[b] Seed moisture contents did not drop after additional drying.

Table 2. Mean (± SE) composition and percent of oil of <u>Lesquerella fendleri</u> seed grown at five plant populations harvested at day 203 (04/21/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	µg/mg of seeds				
C16 : 0	3.29 ± 0.58a	1.54 ± 0.41a	3.65 ± 1.31a	5.09 ± 3.43a	2.00 ± 0.44a
C16 : 1	2.29 ± 0.47a	1.05 ± 0.38b	1.61 ± 0.70ab	1.40 ± 1.11ab	1.30 ± 0.41ab
C18 : 0	3.01 ± 1.23a	0.66 ± 0.29ab	0.21 ± 0.14b	0.24 ± 0.16b	0.59 ± 0.30ab
C18 : 1	22.40 ± 8.30ab	11.09 ± 3.25a	59.45 ± 29.70a	22.15 ± 16.21a	12.38 ± 2.97a
C18 : 2	11.21 ± 3.53b	6.38 ± 1.80a	33.65 ± 16.44a	20.23 ± 16.20a	6.76 ± 1.53a
C18 : 3	19.74 ± 7.78b	7.11 ± 2.27b	111.54 ± 73.40a	22.17 ± 18.45b	9.23 ± 2.41b
C20 : 1OH	62.46 ± 36.14a	25.80 ± 7.60a	94.11 ± 50.96a	61.06 ± 53.43a	21.84 ± 6.74a
C20 : 2OH	4.70 ± 3.30a	0.60 ± 0.60a	0.00 ± 0.00	0.00 ± 0.00	0.97 ± 0.51a
Total (%)	12.90 ± 2.06b	5.40 ± 1.46c	30.40 ± 8.13a	13.23 ± 2.71b	5.51 ± 1.46c

a. Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 3. Means (± SE) percent of fatty acids of <u>Lesquerella fendleri</u> seed grown at five plant populations harvested at day 203 (04/21/94).[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	% Fatty acids				
C16 : 0	4.94 ± 1.41a	3.65 ± 1.08a	3.53 ± 2.32a	8.73 ± 2.33a	4.30 ± 0.87a
C16 : 1	2.94 ± 0.47a	2.14 ± 0.63a	2.18 ± 0.76a	5.12 ± 4.50a	2.67 ± 0.79a
C18 : 0	4.63 ± 3.41a	0.98 ± 0.34a	0.34 ± 0.25a	0.53 ± 0.38a	0.71 ± 0.34a
C18 : 1	21.30 ± 1.81a	21.13 ± 2.96a	24.16 ± 4.07a	22.75 ± 4.65a	23.74 ± 1.47a
C18 : 2	12.66 ± 1.88a	13.04 ± 2.58a	13.05 ± 2.18a	19.05 ± 4.73a	13.45 ± 1.29a
C18 : 3	17.57 ± 1.20b	13.29 ± 1.88b	26.68 ± 1.33a	11.40 ± 3.04b	17.07 ± 1.67b
C20 : 1OH	34.51 ± 6.99a	45.17 ± 7.33a	29.98 ± 5.63a	32.41 ± 11.53a	36.84 ± 3.65a
C20 : 2OH	1.43 ± 0.92a	0.57 ± 0.57a	0.00 ± 0.00	0.00 ± 0.00	1.18 ± 0.57a

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 4. Means (± SE) composition and percent of oil of <u>Lesquerella fendleri</u> seed grown at five plant populations at day 229 (05/17/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	µg/mg of seeds				
C16 : 0	5.75 ± 2.28a	3.40 ± 0.33a	3.47 ± 0.15a	3.31 ± 0.26a	4.09 ± 0.11a
C16 : 1	2.31 ± 0.16a	2.38 ± 0.22a	2.57 ± 0.16a	2.26 ± 0.18a	2.60 ± 0.12a
C18 : 0	3.17 ± 0.27a	3.95 ± 0.40a	3.67 ± 0.14a	3.27 ± 0.30a	3.93 ± 0.45a
C18 : 1	31.58 ± 4.50a	41.42 ± 1.83a	40.86 ± 2.15a	32.50 ± 4.93a	47.73 ± 1.45a
C18 : 2	15.81 ± 1.50a	19.17 ± 1.83a	18.73 ± 0.87a	21.05 ± 4.91a	21.15 ± 0.46a
C18 : 3	32.37 ± 2.72a	37.75 ± 3.57a	38.13 ± 1.81a	31.36 ± 3.19a	45.27 ± 1.51a
C20 :1OH	109.64 ± 11.96b	135.5 ± 13.76a	130.04 ± 7.01b	120.79 ± 14.48b	155.9 ± 6.85a
C20 :2OH	8.51 ± 2.06a	10.00 ± 1.06a	9.52 ± 0.82a	8.59 ± 1.52a	12.80 ± 0.87a
Total (%oil)	20.91 ± 2.06b	25.35 ± 2.54ab	24.69 ± 1.20b	22.31 ± 2.16b	29.35 ± 0.96a

[a] Means fatty acids within a row followed by the same letter are not significantly different, P ≤ 0.05, by Duncan's Multiple Range Test.

Table 5. Means (± SE) percent of fatty acids of <u>Lesquerella fendleri</u> seed grown at five plant populations harvested at day 229 (05/17/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	% Fatty acids				
C16 : 0	2.61 ± 1.11a	1.36 ± 0.04a	1.41 ± 0.07a	1.53 ± 0.11a	1.40 ± 0.06a
C16 : 1	1.23 ± 0.17a	0.97 ± 0.07a	1.05 ± 0.08a	1.04 ± 0.07a	0.90 ± 0.06a
C18 : 0	1.54 ± 0.04a	1.55 ± 0.02a	1.50 ± 0.06a	1.51 ± 0.11a	1.33 ± 0.15a
C18 : 1	15.26 ± 1.76a	16.21 ± 0.24a	16.55 ± 0.35a	15.29 ± 1.96a	16.31 ± 0.43a
C18 : 2	7.72 ± 0.40a	7.62 ± 0.17b	7.61 ± 0.29a	9.15 ± 1.38a	7.23 ± 0.43a
C18 : 3	15.85 ± 0.65a	14.95 ± 0.27a	15.48 ± 0.18a	14.40 ± 1.01a	15.46 ± 0.43a
C20 : 1OH	51.70 ± 1.85a	53.37 ± 0.47a	52.58 ± 0.54a	53.30 ± 1.76a	53.00 ± 1.00a
C20 : 2OH	4.05 ± 6.25a	3.93 ± 0.14a	3.82 ± 0.20a	3.77 ± 0.39a	4.34 ± 0.17a

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 6. Means (± SE) composition and percent of oil of <u>Lesquerella fendleri</u> seed grown at five plant populations at day 243 (06/01/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	µg/mg of seeds				
C16 : 0	3.76 ± 0.23a	3.38 ± 0.13a	3.36 ± 0.22a	3.50 ± 0.24a	3.42 ± 0.15a
C16 : 1	2.45 ± 0.18a	2.07 ± 0.14a	2.31 ± 0.20a	2.36 ± 0.22a	2.16 ± 0.17a
C18 : 0	4.17 ± 0.25a	3.63 ± 0.18a	3.84 ± 0.18a	4.04 ± 0.19a	3.72 ± 0.12a
C18 : 1	41.42 ± 2.53a	37.57 ± 1.73a	38.74 ± 2.15a	40.95 ± 2.04a	37.59 ± 1.40a
C18 : 2	19.22 ± 1.30a	17.07 ± 0.71a	18.29 ± 0.80a	19.34 ± 0.96a	18.10 ± 0.78a
C18 : 3	39.69 ± 2.52a	34.53 ± 1.68a	35.86 ± 1.25a	38.95 ± 1.59a	34.96 ± 1.05a
C20 :1OH	135.50 ± 10.64a	111.0 ± 10.74b	126.50 ± 7.75b	140.63 ± 7.29a	110.6 ± 13.7b
C20 :2OH	12.04 ± 1.18a	8.39 ± 0.86a	9.49 ± 0.86a	11.10 ± 0.71a	8.94 ± 0.37a
Total (%oil)	25.82 ± 1.98a	21.76 ± 1.47b	23.83 ± 1.18a	26.08 ± 1.24a	21.95 ± 1.59b

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 7. Means (± SE) percent of fatty acids of *Lesquerella fendleri* seed grown at five plant populations harvested at day 243 (06/01/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	% Fatty acids				
C16 : 0	1.48 ± 0.07a	1.60 ± 0.12a	1.41 ± 0.07a	1.33 ± 0.05a	1.64 ± 0.16a
C16 : 1	0.95 ± 0.04a	0.96 ± 0.07a	0.98 ± 0.09a	0.89 ± 0.06a	1.02 ± 0.10a
C18 : 0	1.63 ± 0.05a	1.70 ± 0.09a	1.62 ± 0.06a	1.55 ± 0.03a	1.78 ± 0.18a
C18 : 1	16.28 ± 0.54a	17.60 ± 0.88a	16.28 ± 0.55a	15.70 ± 0.27a	17.85 ± 1.46a
C18 : 2	7.58 ± 0.30a	8.04 ± 0.50a	7.71 ± 0.34a	7.43 ± 0.21a	8.70 ± 0.98a
C18 : 3	15.56 ± 0.44a	16.20 ± 0.93a	15.13 ± 0.40a	14.98 ± 0.23a	16.75 ± 1.61a
C20 : 1OH	51.79 ± 1.49a	50.10 ± 2.29a	52.90 ± 1.19a	53.86 ± 0.58a	48.00 ± 4.80a
C20 : 2OH	4.74 ± 0.42a	3.79 ± 0.25a	3.95 ± 0.26a	4.25 ± 0.20a	4.24 ± 0.35a

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 8. Means (± SE) composition and percent of oil of <u>Lesquerella fendleri</u> seed grown at five plant populations harvested at day 264 (06/21/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	µg/mg of seeds				
C16 : 0	3.10 ± 0.08a	3.50 ± 0.16a	2.94 ± 0.18a	3.48 ± 0.19a	3.18 ± 0.26a
C16 : 1	2.07 ± 0.06a	2.28 ± 0.12a	1.94 ± 0.07a	2.50 ± 0.10a	2.14 ± 0.16a
C18 : 0	3.04 ± 0.41a	4.00 ± 0.27a	3.04 ± 0.16a	3.87 ± 0.23a	3.46 ± 0.29a
C18 : 1	32.00 ± 1.37b	37.50 ± 2.18a	30.96 ± 1.52b	38.77 ± 2.16a	31.31 ± 4.46b
C18 : 2	14.76 ± 0.43b	17.94 ± 1.04a	14.11 ± 0.76b	17.60 ± 0.81a	18.16 ± 2.54a
C18 : 3	30.20 ± 1.10a	37.34 ± 2.41a	30.25 ± 1.48a	37.58 ± 1.76a	32.87 ± 2.52a
C20 :1OH	106.00 ± 4.73a	125.10 ± 9.49a	101.48 ± 7.66a	125.44 ± 8.64a	113.9 ± 10.1a
C20 :2OH	9.77 ± 1.42b	9.30 ± 0.56b	17.47 ± 8.95a	10.51 ± 0.77b	9.16 ± 0.79b
Total(%)	20.09 ± 0.81a	23.69 ± 1.57a	20.21 ± 1.47a	23.97 ± 1.39a	21.41 ± 1.81a

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

Table 9. Means (± SE) percent of fatty acids of *Lesquerella fendleri* seed grown at five plant populations harvested at day 264 (06/21/94) after sowing.[a]

	Plant populations/ha				
	250,000	500,000	750,000	1,000,000	1,500,000
Fatty acids	% Fatty acids				
C16 : 0	1.55 ± 0.05a	1.50 ± 0.04a	1.48 ± 0.08a	1.46 ± 0.07a	1.50 ± 0.04a
C16 : 1	1.04 ± 0.03a	0.97 ± 0.03a	0.98 ± 0.06a	1.04 ± 0.04a	1.01 ± 0.03a
C18 : 0	1.50 ± 0.19a	1.70 ± 0.04a	1.53 ± 0.07a	1.61 ± 0.03a	1.61 ± 0.03a
C18 : 1	15.94 ± 0.35b	15.90 ± 0.29a	15.61 ± 0.83a	16.23 ± 0.47a	14.60 ± 1.61a
C18 : 2	7.40 ± 0.17a	7.61 ± 0.14a	7.10 ± 0.32a	7.40 ± 0.15a	8.64 ± 1.18a
C18 : 3	15.05 ± 0.22a	15.79 ± 0.16a	15.22 ± 0.67a	15.78 ± 0.38a	15.47 ± 0.24a
C20 : 1OH	52.71 ± 0.51a	52.51 ± 0.62a	50.43 ± 2.09a	52.10 ± 0.96a	52.90 ± 0.73a
C20 : 2OH	4.82 ± 0.63b	4.00 ± 0.20b	7.64 ± 1.22a	4.35 ± 0.12b	4.27 ± 0.09b

[a] Means fatty acids within a row followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Multiple Range Test.

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APPENDIX C. EFFECT OF IRRIGATION TERMINATION DURING THE REPRODUCTIVE GROWTH ON YIELD OF *Lesquerella fendleri*

EFFECT OF IRRIGATION TERMINATION DURING THE REPRODUCTIVE GROWTH ON YIELD OF *Lesquerella fendleri*

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EFFECT OF IRRIGATION TERMINATION DURING THE REPRODUCTIVE GROWTH ON YIELD OF *Lesquerella fendleri*

ABSTRACT

High water use demands of *Lesquerella fendleri*, coincide with its reproductive growth in early spring and summer. Limitation of irrigation during this stage has been suggested in order to increase water use efficiency and minimize cost of production. This research was undertaken to study the effects of limited irrigations during the reproductive phase of *Lesquerella* on seed yield and vegetative growth. *Lesquerella fendleri* was grown from 24 November 1993 through 4 June 1994 under a shadehouse at The University of Arizona, Campbell Agricultural Center. Bulk seed of the 1993 harvest (June) were hand sown in 100 pots (3.8 L) using a mixture containing 50% sand, 15% clay, 15% vermiculite, 10% perlite, and 10% peat moss. Single potted plants were grouped 65 days after sowing (DAS) to form a randomized complete block design with 5 treatments and 20 replications. At flowering, plants were isolated under a zinc roof to exclude rainfall, and to impose early termination of irrigation to study their effect on yield in *Lesquerella*. Four irrigation terminations were applied at 123, 129, 136, and 143 DAS and termed treatments T4, T3, T2, and T1, respectively. The control (T0) treatment was hand irrigated weekly from day 123 to day 194 after sowing. During that period, soil moisture content, amount of

evapotranspiration, and applied irrigations were determined for all pots until plant death. Termination of irrigation at 123 (T4) and 129 (T3) DAS resulted in a decrease in flowering and in silique formation. Overall, early imposition of water deficit decreased seed weight, the number of seeded (filled) siliques and seed yield for all treatments. The number of seeds per plant was not reduced for T2 (136 DAS). The water deficit also reduced plant height for all treatments, the number of branches and taproot length for T1, T3, and T4, and the width for T4. Water use efficiency for seed production was similar for T2 and the control. Limitation of irrigation, however, for other treatments did not increase water use efficiency.

INTRODUCTION

Lesquerella is currently cultivated in Arizona from late September through late June, requiring about 50 cm of applied water. Approximately, half of the plants' consumption is derived from irrigation, and the remaining half is supplied from late summer and winter precipitations. Most of the irrigation is applied during reproductive growth, beginning in mid-February and extending through early June. These are also times when rising air temperatures promote high evaporation losses. The increasing cost of pumped water and its relative availability emphasizes the need for conservation and efficiency of water use in the southwestern U. S. (Mclaughlin, 1985). It has been suggested that in arid environments, water conservation could partially be achieved by limitating irrigation during periods of great evaporative losses (Stewart et al., 1983).

However, studies involving moisture deficits have shown that yield depressions are inevitable when irrigation or moisture becomes limited during plant growth in cotton (Gossypium hirsutum L.) (Guinn and Mauney, 1982a, b), sunflower (Helianthus annus L.)(Connor et al., 1985), rapeseed (Brassica napus L.) and turnip rape (Brassica rapa L.) (Mailer and Cornish, 1987). These depressions continue to be observed when reduced watering is imposed during the reproductive growth alone in soybean (Glycine max L.)(Sionit and Kramer, 1977; Smiciklas et al., 1992; Eck et al., 1987), sunflower (Connor et al., 1985), rapeseed, and turnip rape (Mailer and Cornish, 1987). Yield component analysis has demonstrated that water deficit during reproductive growth negatively affected yield by reducing the reproductive load (Smiciklas et al., 1992), primarily through reduced flower production and retention (Sionit and Kramer, 1977), pod abortion at late flowering and pod development (Shaw and Laing, 1966), seed number (Smiciklas et al., 1992) and seed weight reduction, mostly at formation and during filling in both soybean and rapeseed (Mailer and Cornish, 1987; Smiciklas et al., 1992).

The effect of water stress on yield performance of

Lesquerella has not been reported. This study was undertaken to investigate the impact of induced moisture stress during reproductive growth on seed yield in *Lesquerella fendleri*.

MATERIALS AND METHODS

This experiment was conducted from November 1993 through June 1994 in a shadehouse at The University of Arizona, Campbell Agricultural Center. Bulk seed of *Lesquerella fendleri* harvested in 1993 (June) were hand sown on 24 November 1993 in 100 pots (3.8 L), using a soil mixture of 50% sand, 15% clay, 15% vermiculite, 10% perlite, and 10% peat moss. Seedlings were thinned 65 days after sowing (DAS) to one plant per pot. These individual plants, grown until this time under winter rainfall (8cm) and hand irrigated moisture (12cm), were randomly divided to form a randomized complete block design with 5 treatments and 20 replications beginning at flowering.

Prior to the application of treatments, all plants were isolated under a zinc roof about 2 m above ground to prevent wetting from rainfall. The treatments consisted of early termination of irrigation or moisture until harvest (irrigation and/or rainfall) starting at 123 DAS (beginning of flowering) and extending to 129, 136, and 143 DAS. These regular intervals insured that a difference of one irrigation existed between successive treatments. The earliest treatment, subjected to moisture stress and the greatest water deficit, was termed treatment 4 (T4), followed in descending order by treatments 3 (T3), 2 (T2), and finally treatment 1 (T1). The control (T0) was irrigated weekly from 123 DAS to the time of harvest at 194 DAS. T4, operated only on stored water accumulated from irrigation and rainfall received following sowing until the time when plants were placed under the zinc roof (123 DAS).

The moisture status of the pots was determined weekly by weighing all pots 24 hr before and after irrigation using a standard scale. The evapotranspiration losses were estimated by the same method. Weight results were expressed in soil moisture content at depths of 0 to 10 cm following the gravimetric method described by Donahue et al. (1983).

Measurements of each plant's height, width, number of branches, and root length were made at 130 and 194 DAS to determine the impacts of different moisture regimes on vegetative growth. Flower and silique production, were counted every two days, but their values were reported on a weekly basis. The number of seeded siliques, seeds/silique, and seed weight were determined at final harvest at 194 DAS.

The experiment was analyzed as a randomized complete block design using the SAS package (SAS Institute, 1988). Means separation was based on Duncan's Multiple Range Test at 0.05 level probability.

RESULTS AND DISCUSSION

The estimated monthly amount of irrigation and evapotranspiration are shown in Figs 1-5. Generally, evapotranspiration values were higher than the added water, indicating that even the control experienced some degree of water stress. Irrigation in the control (T0) provided 99% of evapotranspiration losses in April, dropped to 90% in May, and was 94% for the only irrigation in June. The corresponding values for the stressed treatments were lower and represented 69, 47, and 40% for T1, T2, and T3, respectively, during April. T4 was not considered since there was no irrigation and precipitation after isolation (123 DAS).

The apparent increase in evapotranspiration in May and June for the control (T0) were associated with the rising air temperatures during these months. Day and night time average temperatures recorded at the Campbell Agricultural Center meteorological station were respectively, 32.6° and 17.8°C in May and 39.4°C and 17.8°C in June while these averages were only 29°C and 10.3°C in April.

The response to water stress on Lesquerella growth was evident (Table 1). Reduced or withheld irrigation between 123 and 150 DAS resulted in a decrease in plant height (19-29%) for all stressed treatments, and a decrease in width by 25% in T4 relative to the control (T0). Reported height decreases have been observed under moisture stress during the reproductive growth in soybean (Glycine max L.) (Thompson, 1977; Eck et al., 1987).

The reduction of width in T4 suggested that the canopy continued to expand 7 to 10 days after the beginning of flowering. The more generalized effect of water stress in height showed that growth extended about a month into the reproductive stage. Field studies found that height continues to increase 15 to 30 days after width development has stopped (Appendix A).

Soil moisture deficits reduced the number of branches by 23-25% (Table 2) and taproot length/plant by 13-17%, except in T2 (Table 1). The similarity in branch and root production between the control and T2 raises an interesting question whether the vegetative growth of Lesquerella was limited by the total amount of applied water or the application of water that surpasses evapotranspiration losses at a specific time. T1 had less growth than T2, although it received more irrigation. The difference in growth behavior between T2 and the other stressed treatments suggests that water deficits were more critical during the first 2 to 3 weeks of flowering than they were before or after this period. Therefore, the growth advantage observed for T2 could be explained by the excessive watering of about 2 mm above evaporation losses at 136 DAS (Fig. 3). This irrigation probably enhanced root growth and increased water uptake through the exploration of deeper available soil water fraction. Improved plant water status in a limited soil moisture environment have been positively correlated with root size and available soil water fraction (Gajri and Prihar, 1985).

Cumulative flowers and siliques produced/plant are presented in Table 2. T3 and T4 had significantly lower production of flowers than T0, T1, and T2. The relative production of flowers of T3 compared to T0 was 68% and T4 was 63%. The lower production in these treatments resulted from the early death of plants between 128 and 158 DAS. During this interval nearly all plants of T3 and 90% of T4 plants died (data not shown) when soil moisture was below 4% (Figs. 4-5). The number of siliques formed/plant followed the same pattern as flowering; with T3 and T4 producing a significantly lower number of siliques then T0, T1, and T2 (Table 2). T3 produced 62% of the quantity of siliques observed in the control (T0) and T4 produced about 34%.

The proportion of flowers that became siliques were 72, 55, 58, 63, and 38%, respectively, for the control, T1, T2, T3, and T4 (Table 2). The value under field growing conditions is 86% or more (Appendix A).

There was only a small portion of siliques that contained seeds at harvest. Flowering that translated into seeded siliques represented 11% for the control. The values for stressed T1, T2, T3, and T4 were, respectively, 4.0, 3.4, 1.6, and 3.0%. These low percentage reflected the inadequacy of all irrigation regimes in this study. The number of seeded siliques/plant showed significant differences among treatments (Table 3). The control produced the highest, about 10 times more seeded siliques than either T3 or T4 (lowest). However, the number of seeds within these siliques did not differ only between T2 and the control. Seed weight (yield) on the other hand, was higher for the control. The average seed weight demonstrated marked differences among treatments. The control produced the heaviest seeds while the highest seed number/silique was found in T3. The seed characteristics of the control were translated into greater yield when compared to other treatments. These data support other findings that reported that stress during the reproductive phase limited seed production by reducing the number of seeds/pod in soybeans (Smiciklas et al., 1992), and also causing a decrease in seed weight in rapseed (Mailer and Cornish, 1987) and in soybeans (Smiciklas et al., 1992).

The decline in the number of seed/plant observed in this study was related to the inability of stressed treatments to carry to maturity more seeded siliques. This factor was associated with fewer seed produced/silique in T4 (1.4 vs 4.0 for the control). T1 had 5.6 seed/silique and T2 and T3 averaged 7.6 seed/silique; all were higher than the 4.0 seed/silique in the control. The varying responses of the treatments to seed number/silique suggests that the timing of induction of water stress occurred at different growth stages. The earliest imposition of water stress (T4) coincided with the beginning of flowering when plants were able to adjust their reproductive load by reducing the number of seeds and eventually improving seed quality (weight) at harvest. However, the early senescence and drop of leaves beginning 134 DAS (data not shown) and the limited taproot length (5.7-5.8 cm) of plants in moisture depleted soil (Table 1), possibly restricted the photoassimilate supply during seed fill and consequently causing a 67% reduction in seed weight. It has been demonstrated that withholding water at seed fill and at anthesis resulted in rapid decrease in leaf area index through accelerated leaf senescence. Such senescence reduces seed production as it restricts photoassimilate supply during seed formation in rapeseed (Connor et al., 1985). Limitation of reproductive load for the benefit of improved seed quality has been suggested by Smiciklas et al. (1992) during water stress at early flowering as a drought coping mechanism in soybean.

Moisture stress occurring after seed formation has little effect on seed number, but can reduce the seed weight as the competition for available resources is intensified during seed fill (Eck et al., 1987; Smiciklas et al., 1992). The higher number of seed in T1, T2, and T3 indicated that the moisture stress in these treatments occurred after seed formation, and the actual flowers that developed into seed were from those produced during the 128 and 130 DAS counts. All flowers counted at 128 and 130 DAS developed into seed for the control, and T1 developed into seed only 26% of its flower production at 130 DAS. Seeds harvested from T2, T3, and T4 were derived from the 128 DAS flowering count. All of the flowers reached seed maturity for the T2 and only a portion, 42 and 44% reached seed maturity for T3 and T4, respectively.

The reduction in seed weight at harvest of 67, 55, and 75% for T1, T2, and T3, respectively, was associated with the prolonged effects of moisture stress and a strong competition for assimilate for the numerous seed/silique (sink). A study by Egli et al. (1985) in soybean has shown that seed weight declines when limited assimilates are partitioned between several sinks. Additionally, the limited vegetative growth (Tables 1 and 2) with its resulting lower biomass in stressed treatments (data not shown), may have limited the remobilization of assimilate from vegetative tissue to partially support the seed growth as observed in soybean (Israel, 1981).

The estimates of water use efficiency are presented in Table 4. The values were very small for all watering regimes. However, T2 and the control were more efficient in using water than the remaining treatments. Seed production was drastically affected by high evapotranspiration and the fast drying soil (Figs. 1-5). Irrigations did not provide enough water to match evapotranspiration losses. The irrigation volume was low in general (Figs.1-5) and the supply from the soil was limited by rapid drying, averaging 10 to 14%/week, and shallow root systems. The poor plant growth in this study was attributed to limited soil moisture. The effect of such deficit ultimately restricted transpiration and consequently affected productivity as these relations are closely associated in other plants such as peanuts (Simmonds and Williams, 1989).

CONCLUSION

Induction of water stress by early termination of irrigation beginning with the onset of flowering and expanded sequentially during the following three weeks, resulted in a reduction in both vegetative and reproductive growth. Moisture stress reduced plant height, number of branches, and root length. It also reduced flowering rate and silique formation. The combination of vegetative and reproductive growth limitations were translated into severe seed yield depression, through the reduction of seed weight, number of seeded siliques, and the number of seeds/plant. Treatment 2 (T2) was the least affected by moisture deficit. The drought resistance of this treatment may have been associated with adequate watering of plants at the time of seed formation (136 DAS), which possibly enhanced an increased root length for deeper soil water exploration. The water use efficiency for seed production of T2 was similar to that of the control, implying that extension of irrigation to harvest does not necessarily increase economic returns. It appears, that management practices should focus on heavy watering of plants during the first 2 to 3 weeks of flowering, rather than to provide latter abundant irrigations at times when these may not be economically feasible.

Table 1. Means (±SE) final height, width and taproot length/plant of Lesquerella fendleri in shadehouse at five watering regimes in 1993-94.[a]

Irrigation treatments[c]	Final height[b] (cm)	Final width[b] (cm)	Taproot length (cm)
T0	30.0±3.8a	10.3±2.1a	6.8±0.8a
T1	20.1±3.7b	8.0±1.6ab	5.7±0.6b
T2	24.1±2.9b	9.0±1.7ab	6.2±0.4ab
T3	24.0±2.96b	8.0±1.5ab	5.9±0.5b
T4	21.0±1.8b	7.7±1.5b	5.8±0.5b

[a] Means within a column followed by the same letter are not significantly different, P ≤0.05, by Duncan's Multiple Range Test.

[b] No differences in plant height (15cm) and width (6cm) at the start of moisture stress 123 DAS (April 2, 1994).

[c] T0 = Weekly irrigated plants from beginning of flowering to harvest (10 weeks)
T1 = Weekly irrigated plants during the first 21 days after beginning of flowering
T2 = Weekly irrigated plants during the first 14 days after beginning of flowering
T3 = Weekly irrigated plants during the first 7 days after beginning of flowering
T4 = Terminated wetting (rainfall and irrigation) at the beginning of flowering (123 DAS)

Table 2. Means (±SE) number final branches, cumulative number of flowers and siliques/plant of <u>Lesquerella fendleri</u> in shadehouse at five watering regimes in 1993-94.[a]

Irrigation treatments[c]	Number of branches[b]	Number of flowers	Number of siliques
T0	7.0±1.1a	41±2.8a	30.±10.8a
T1	5.0±0.5b	36±2.3a	19±7.4a
T2	6.0±0.5ab	41±1.7a	24±4.5a
T3	5.0±0.6b	28±1.3b	18±5.4b
T4	5.0±0.7b	26±1.3b	10±4.7b

[a] Means within a column followed by the same letter are not significantly different, $P \leq 0.05$, by Duncan's Range test.

[b] No difference in the number of branches/plant (5 branches) at the start of moisture stress 129 DAS (April 2, 1994).

[c] T0 = Weekly irrigated plants from beginning of flowering to harvest (10 weeks)
T1 = Weekly irrigated plants during the first 21 days after beginning of flowering
T2 = Weekly irrigated plants during the first 14 days after beginning of flowering
T3 = Weekly irrigated plants during the first 7 days after beginning of flowering
T4 = Terminated wetting (rainfall and irrigation) at the beginning of flowering (123 DAS)

Table 3. Mean (±SE) number and weight of seeds/plant of *Lesquerella fendleri* in shadehouse at five watering regimes in 1993-94.[a]

Irrigation treatments[b]	Number of seeded siliques	Seed weight (mg)	Number of seeds	Average seed weight (mg)
T0	3.3±3.0a	4.9±3.0a	11.7±6.2a	0.40±0.2a
T1	0.8±0.7b	0.6±0.4b	4.5±3.2b	0.13±0.1c
T2	0.8±0.7b	1.1±0.9b	6.1±4.0ab	0.18±0.1b
T3	0.3±0.2c	0.21±0.2b	2.3±1.4b	0.10±0.08d
T4	0.3±0.3c	0.05±0.05b	0.4±0.4b	0.13±0.1c

[a] Means within a column followed by the same letter are not significantly different, $P \leq 0.05$ by Duncan's Multiple Range Test.

[b] T0 = Weekly irrigated plants from beginning of flowering to harvest (10 weeks)
T1 = Weekly irrigated plants during the first 21 days after beginning of flowering
T2 = Weekly irrigated plants during the first 14 days after beginning of flowering
T3 = Weekly irrigated plants during the first 7 days after beginning of flowering
T4 = Terminated wetting (rainfall and irrigation) at the beginning of flowering (123 DAS)

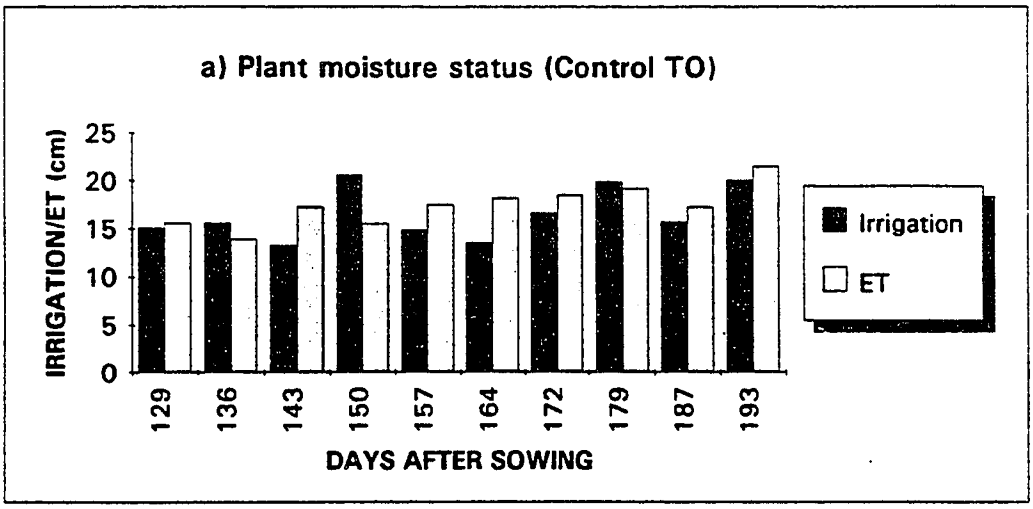
Table 4. Post flowering amount of irrigation, evapotranspiration (mm) and water use efficiency for Lesquerella fendleri in shadehouse at five wetering regimes in 1993-94.[a]

Irrigation treatments[b]	Applied irrigation	Evapotranspiration (mm)	Yield (mg/plant)	Water use efficiency (mg seed/mm water)
T0	165.4	174.7	4.9	0.030
T1	44.0	63.6	0.6	0.014
T2	31.2	49.0	1.1	0.035
T3	14.3	35.3	0.21	0.015
T4	0.0	21.3	0.05	-

[a] Plants received 80 mm of rain and 120 mm of applied irrigation prior to the start of moisture stress 123 DAS (March 25, 1994).

[b] T0 = Weekly irrigated plants from beginning of flowering to harvest (10 weeks)
T1 = Weekly irrigated plants during the first 21 days after beginning of flowering
T2 = Weekly irrigated plants during the first 14 days after beginning of flowering
T3 = Weekly irrigated plants during the first 7 days after beginning of flowering
T4 = Terminated wetting (rainfall and irrigation) at the beginning of flowering (123 DAS)

\- Undetermined water use efficiency because of no post flowering irrigation



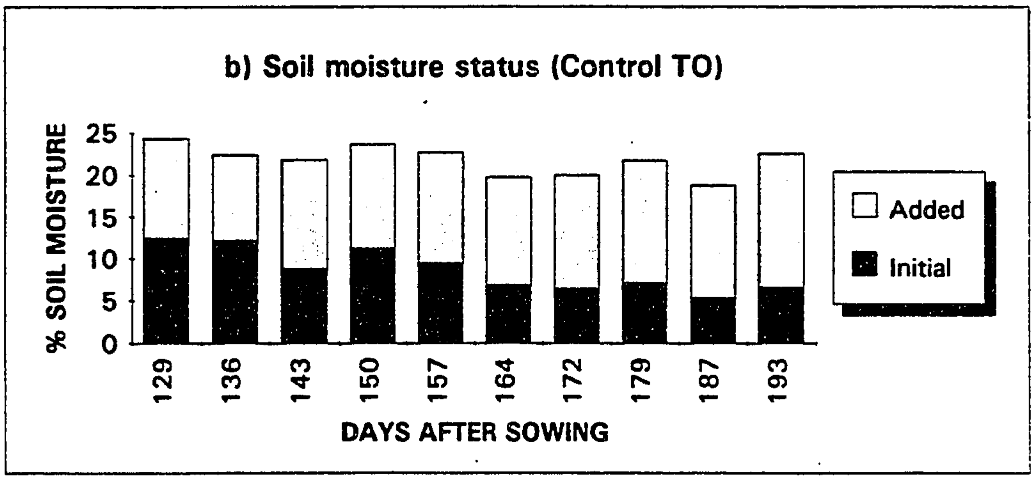


Figure 1. Post-flowering watering regime of Lesquerella fendleri grown in shadehouse in 1993-94 for the control treatment (T0). Weekly irrigated plants from 2 April (beginning of flowering) through 6 June 1994 (maturity harvest) (10 weeks).
a) Weekly irrigation and post irrigation (7 days) cumulative evapotranspiration.
b) Change in soil moisture after irrigation (added).

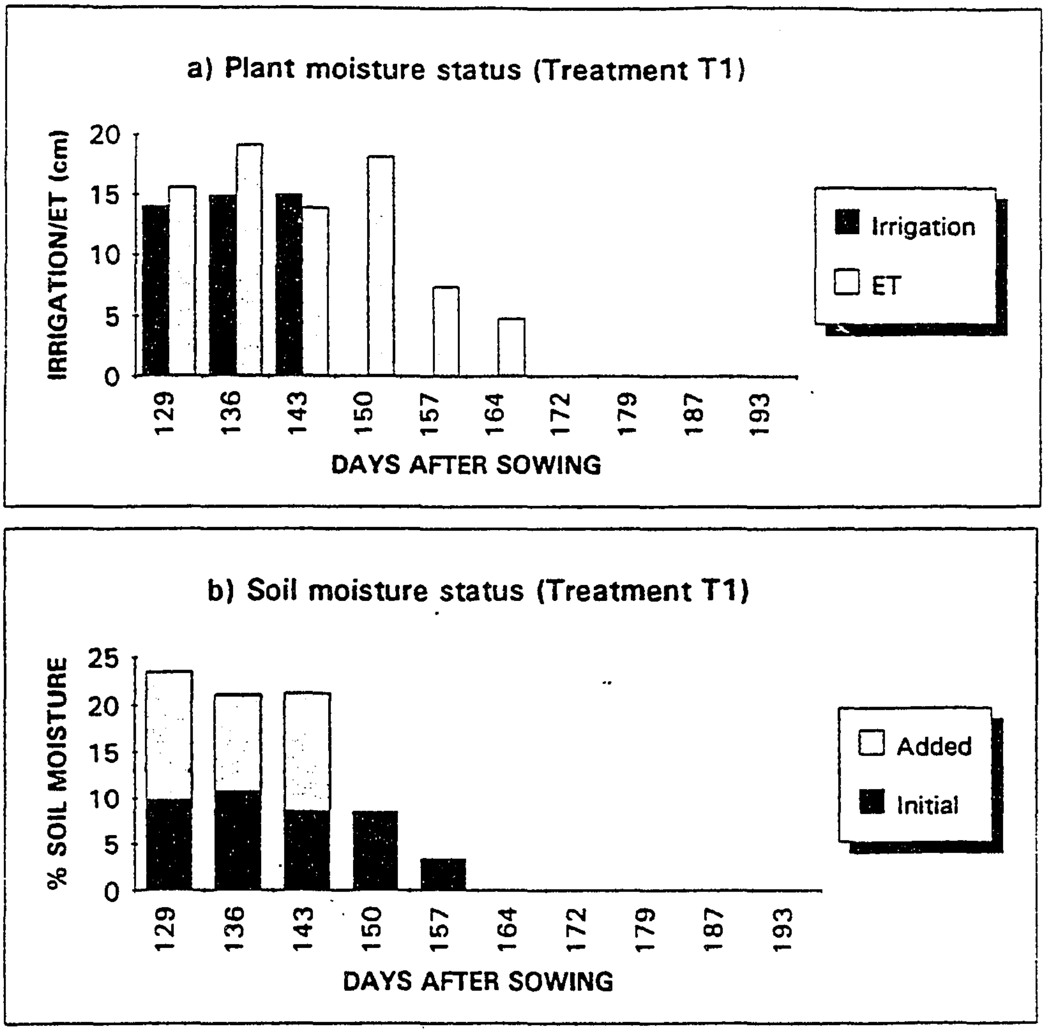


Figure 2. Post-flowering watering regime of Lesquerella fendleri grown in shadehouse in 1993-94 for treatment one (T1). Weekly irrigated plants from 2 April (beginning of flowering) through 23 April 1994 (end of flowering) (3 weeks).
a) Weekly irrigation and post irrigation (7 days) cumulative evapotranspiration.
b) Change in soil moisture after irrigation (added).

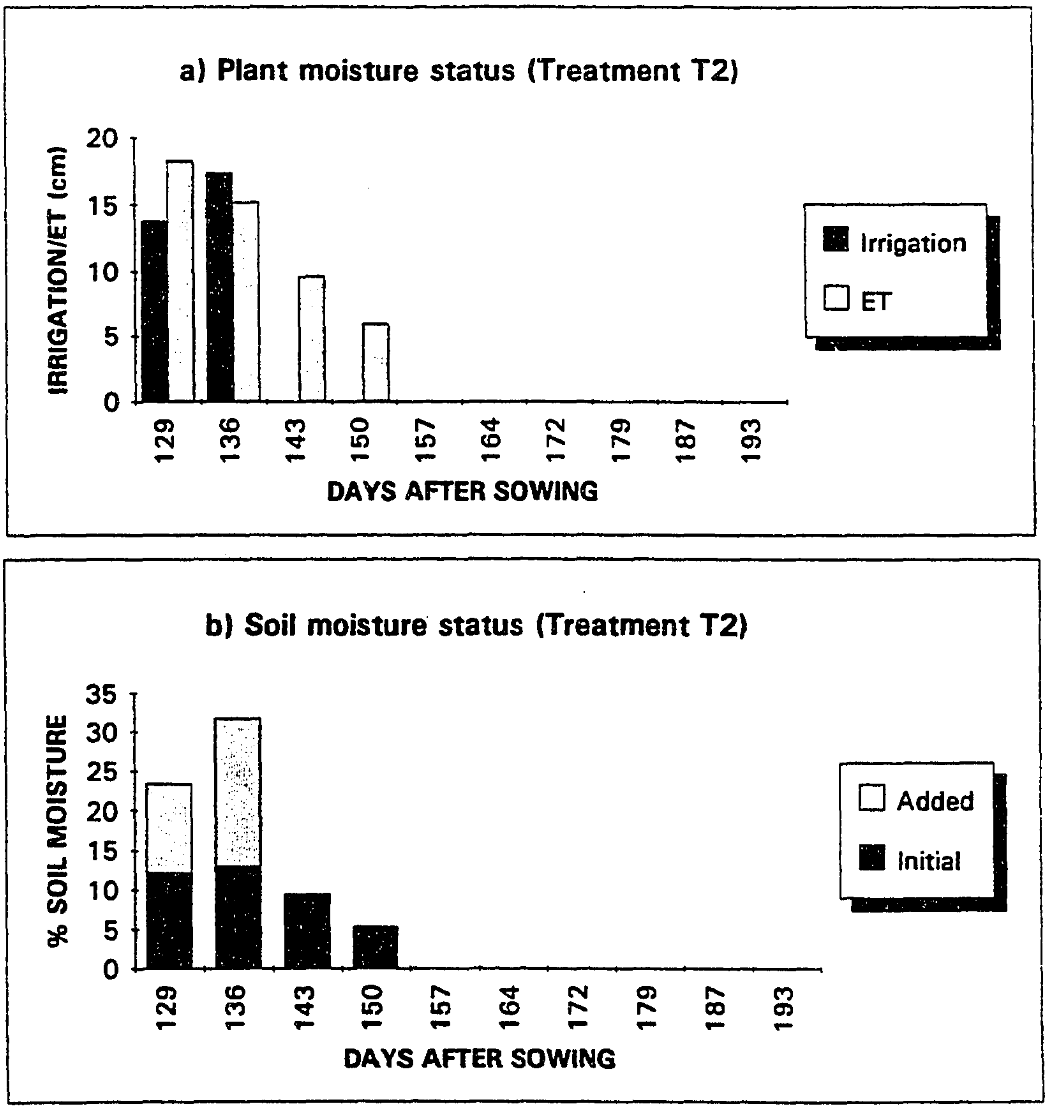
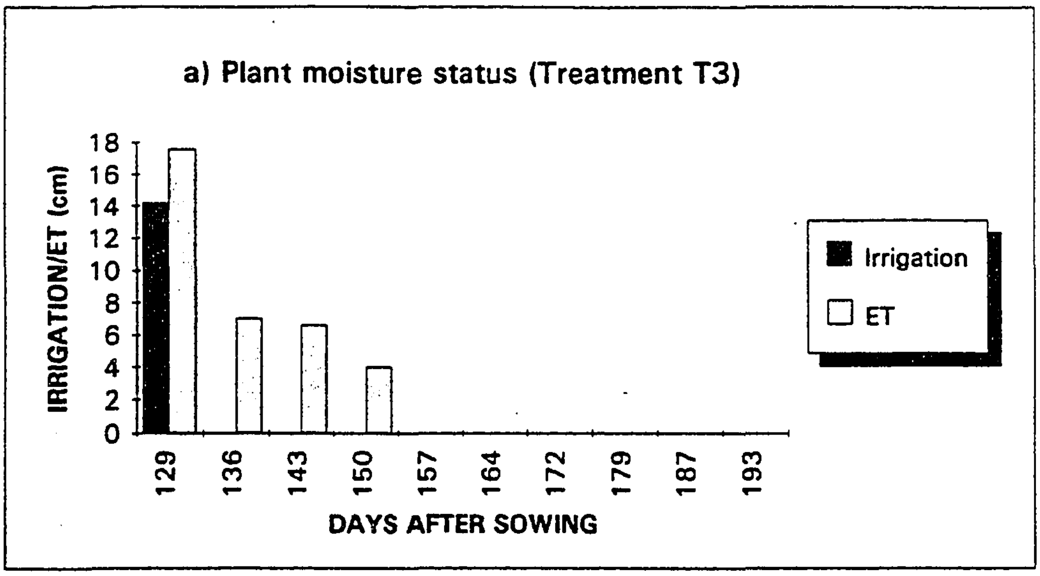


Figure 3. Post-flowering watering regime of Lesquerella fendleri grown in shadehouse in 1993-94 for treatment two (T2). Weekly irrigated plants from 2 April (beginning of flowering) through 16 April 1994 (late flowering) (2 weeks).

a) Weekly irrigation and post irrigation (7 days) cumulative evapotranspiration.

b) Change in soil moisture after irrigation (added).



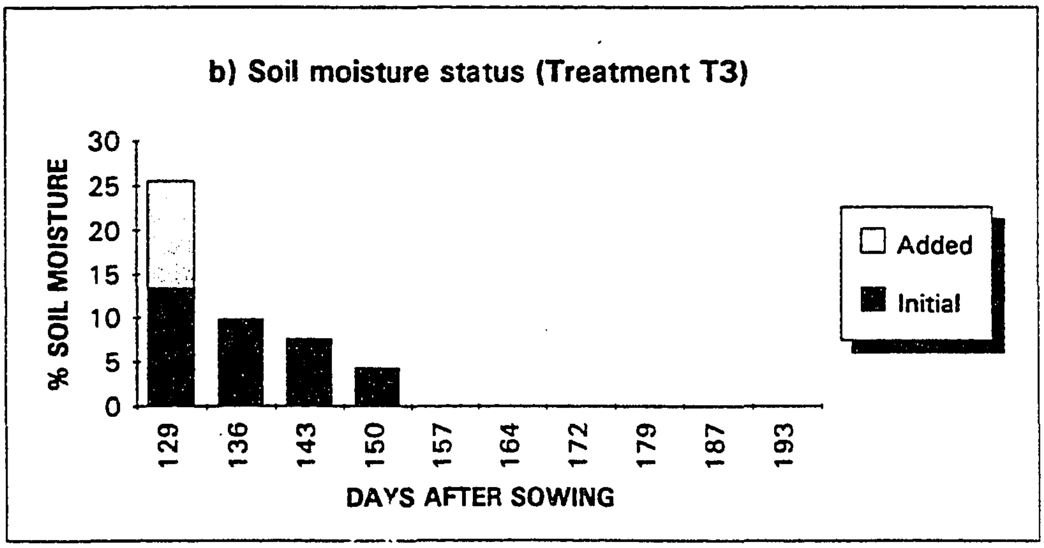


Figure 4. Post-flowering watering regime of Lesquerella fendleri grown in shadehouse in 1993-94 for treatment three (T3). Weekly irrigated plants from 2 April (beginning of flowering) through 9 April 1994 (mid flowering) (1 week).
a) Weekly irrigation and post irrigation (7 days) cumulative evapotranspiration.
b) Change in soil moisture after irrigation (added).

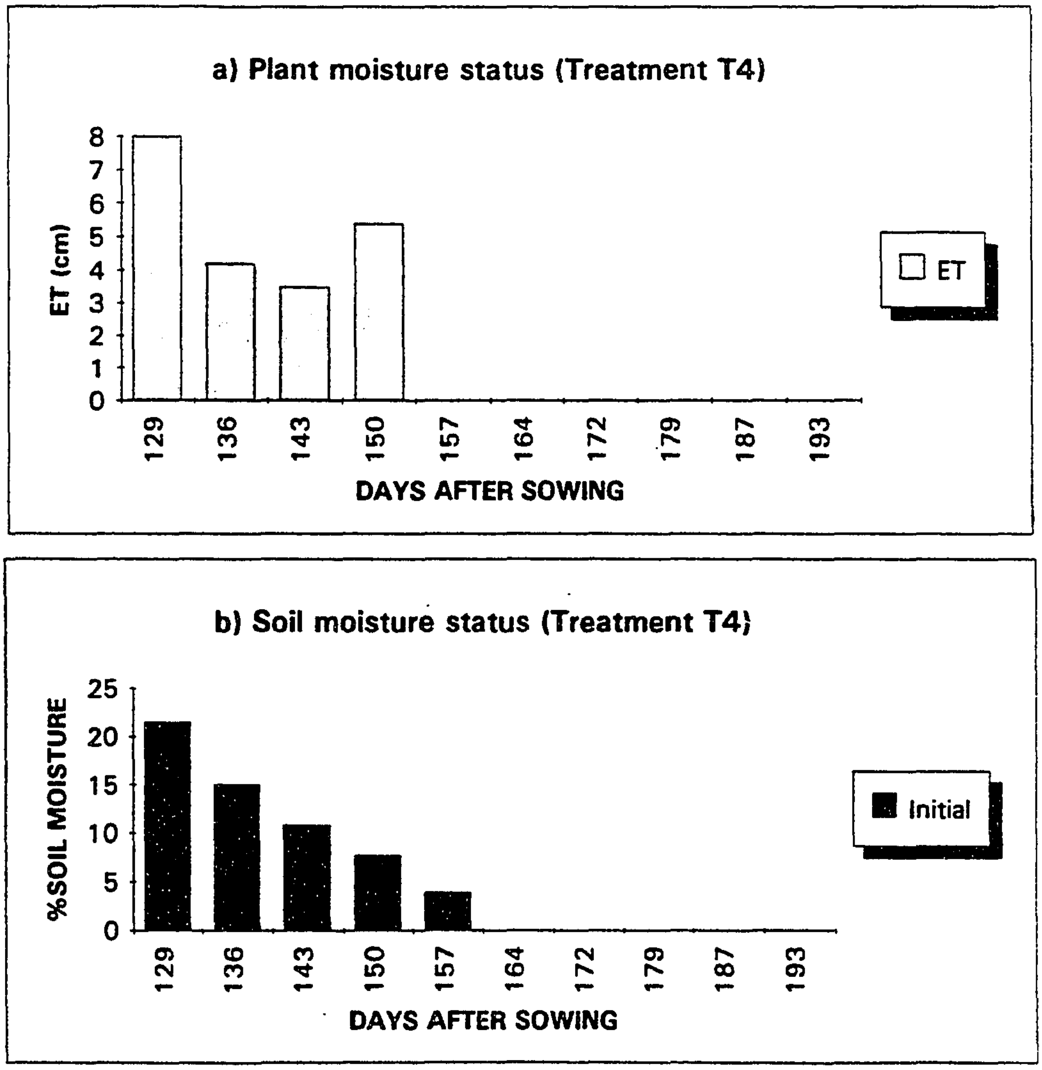


Figure 5. Post-flowering watering regime of Lesquerella fendleri grown in shadehouse in 1993-94 for treatment four (T4). Terminated moisture at beginning of flowering (25 March 1994).
a) Weekly cumulative evapotranspiration of stored moisture (last wetting 123 DAS).
b) Change in soil moisture following drying..

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SUMMARY AND CONCLUSIONS

Early work on density in Lesquerella focused on the of effects of a few vegetative characters (height, width and vegetative weight), and seed weight, harvest index and seed yield at the time of harvest. Such comparisons provided limited information in determining the causes for seed yield variations between the densities studied.

The first experiment of this dissertation (APPENDIX A) expanded vegetative growth comparisons to root length, and dry matter accumulation, and also measured some phenological characters (flowering, senescence) and yield components to assess the effects of density on the plant's vegetative and seed yield performances. The second study (APPENDIX B) evaluated the oil content and composition of developing seeds to identify an appropriate harvest time that will result in an optimum recovery of seed and oil. The last study (APPENDIX C) examined the effect of early termination of irrigation during reproductive growth on seed yield in Lesquerella.

The increase in density of Lesquerella fendleri from 250,000 plants/ha to 500,000, 750,000, 1,000,000 and 1,658,000 plants/ha in 1992-93, resulted in the production of smaller plants as a consequence of decreased plant width, height, and vegetative weight. These reductions were most severe at densities of 1,000,000 and 1,658,000 plants/ha. Increasing density also caused a reduced production of the number of branches/plant. This reduction ultimately lowered the quantity of siliques produced/plant, thus, restricting an individual plant's yielding potential and harvest index. The combined lowering of the number of branches and silique production/plant contributed to the observed reduced vegetative weight of denser treatments relative to the lowest plant population. Finally, density reduced the number of seeds/silique at 750,000 and 1,658,000 plants/ha because of possible competition for assimilates between growth and reproductive organs for the former and rapid seed development or sink competition for the latter. However, increasing density did not affect seed test weight, volume and density (1,000-seed weight).

In contrast, taproot lengths at 500,000 and 750,000 plants/ha were enhanced by the increase in plant density. The greatest enhancement was recorded at the 750,000 plants/ha treatment and this may have contributed to the excessive plant height, while providing an efficient soil water extraction system. Seed yield/ha was also enhanced by increasing density as results of greater production of siliques and seed/unit area, and this clearly suggested the necessity of added plants to improved seed yields. However, density increase paralleled seed shattering, peaking at 1,658,000 plants/ha. The extreme susceptibility of this treatment greatly explained its low seed yield/plant comparable to the production from the 250,000 plants/ha density.

The results of the 1993-94 final harvest (264 DAS) did not reveal differences in seed yield and oil content of the five density treatments. The seed yield increase in the densest control treatment (1,500,000 plants/ha) relative to the low yield of the previous harvest of the control in 1992-93 (1,658,000 plants/ha) were apparently associated with a reduced shattering of seed due to a possible decline in the number of blowing winds and increase in seed maturation attributed to high temperature during seed fill. However, oil content increase in the 250,000 plants/ha treatment in 1993-94 may have resulted from an augmentation of the proportions of mature seeds probably accelerated by early high air temperatures during seed development.

Comparisons of seed oil at 203, 229 and 243 DAS exhibited differences among treatments because the variation in seed ages. The 750,000 plants/ha treatment reached physiological maturity by 203 DAS, followed by the 1,500,000 (control) and 500,000 plants/ha (243 DAS). Phenological observations of flowering in two years (1992-94) and leaf senescence in one year (1992-93) were not useful indicators in determining seed ages. However, counts of siliques/area provided a more accurate account of seed age at the earliest oil sampling.

Harvest at 203 DAS appeared not to be economically feasible because of high seed moisture (83%), poor oil (dominance of the C18 series), low dry matter accumulation in seed, and low oil content (except for the 750,000 plants/ha). Economic limitation of harvest persisted at 229 DAS as a result of high moisture (46% to 53%) and low seed dry matter accumulated. However, harvest was possible at 243 DAS due to increase in dehydration and accumulation of seed dry matter.

Termination of irrigation at the beginning of flowering, demonstrated a reduction in vegetative growth, primarily, height, taproot length and number of branches. The earliest imposition of water stress (beginning of flowering) caused a decreased in plant width and plant stress during the entire first week of flowering, reducing both flower and silique production. The termination of irrigation during reproductive growth most affected seed yield as a consequence of silique abortion and decreased seed weight. These effects were least severe for plants water stressed two weeks after the beginning of flowering. The greater performance (seed + vegetative) of this treatment may have been caused by continuous plant growth on stored soil moisture exceeding evapotranspiration losses. Water use efficiency of the weekly irrigated control was not superior to that of plant water stressed at two weeks after the beginning of flowering. This suggested that watering should focus on the amount of application at specific growth stages, more than extending irrigation to harvest.

The three densest treatments (750,000; 1,000,000; and

1,658,000 or 1,500,000 plants/ha) all appeared well suitable for high seed and oil production. However, under labor restricted environments, direct seeding at a reasonable rate would appear to be the most suitable production system as it eliminates the need for hand thinning. The use of this density would require the minimization of seed shattering losses, especially in wind prone environments. This may be accomplished by early harvest at the start of June. Under limited water conditions, 750,000 plants/ha would appear to be the most suitable density because of its high seed maturing ability (short time to physiological maturation) reduces the needs for extended irrigation and the possible capacity of its long root to extract deep soil water. In contrast, the slow maturing 1,000,000 plants/ha density would be more appropriate under non-limiting water and labor conditions, provided that its higher oil content would compensate for the cost of additional water and labor.

Regardless of the plant density used in the production system, the harvest of Lesquerella seed at 243 DAS would yield maximum economic return as it ensures greater seed production by preventing heavy shattering losses. Additionally, seed contains 3 to 6% more oil than when harvested at later dates (264 DAS), compensating easily for the loss of seed water weight. Abundant irrigations should be applied during seed development to guarantee a high level of seed production.

Under limited water conditions, it would be advisable to irrigate adequately and match evapotranspiration losses during the first couple of weeks following flowering than to extend watering until harvest.

Future Work

The two years of study provided an insight into the effects of five density treatments on the vegetative, seed and oil yield performances of Lesquerella fendleri. However, a number of morphological and physiological behaviors associated with these densities need to be clarified to increase our full understanding. The early termination of irrigation during reproductive growth showed severe seed yield decreases in stressed plants. The extent to which these reductions occurred were amplified by under watering before the termination of these irrigations. The more accurate assessment of early termination of irrigations under field conditions is useful to guide irrigation management. The following questions need to be addressed:

1) Do the increases in root length in the 500,000 and 750,000 plants/ha treatments contribute to the drought resistance mechanism of these plants?

2)How different are the leaf water potentials in moisture depleted soil in the different densities?

3)Why do plants of the different treatments, but of same age, do not reach physiological maturity at the same time, and when exactly does maximum oil accumulation occur?

4)Does the extension of roots in the 750,000 plants/ha density confer an advantage for earliness in oil formation?

5) What temperatures induce an alteration in fatty acid composition in developing seed oil?

6)Why does lesquerolic acid content of early oil forming plants (750,000 plants/ha) drop more slowly than that of late oil forming plants (1,000,000 and 250,000 plants/ha)?

7)When does irrigation termination reduce seed number/silique, and what level of irrigation causes a decline in seed weight?

8)When does seed formation begin after flowering?

9)What level of irrigation produces the greatest water use efficiency?

10)Are silique abortions correlated to water use deficit?