Shallot (*Allium cepa* var. *ascolonicum*) Responses to Plant Nutrients and Soil Moisture in a Sub-humid Tropical Climate

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Abstract

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Shallot requirements of nitrogen, phosphorus and potassium fertilizers were studied under rain-fed and irrigated conditions on heavy clay soils with low to medium organic matter contents in a sub-humid tropical climate of eastern Ethiopia. Influences of varying levels of irrigation water in combination with nitrogen fertilizer were assessed. Impacts of soil moisture stresses at different growth stages of the plant were evaluated in greenhouse and under field conditions. Different types of mulching materials were evaluated for their effect on the shallot crop and some soil characteristics. Parameters of plant growth, yield and bulb quality and storability were assessed in relation to applied treatments.

The results showed the significance of soil moisture for shallot production in the sub-tropical climate. All mulching treatments improved shallot yields during the short season. During the main season, however, straw and clear plastic mulches favoured heavy weed infestation and reduced yields. Black plastic mulches increased yield up to three-fold without negative effects on the quality of bulbs.

Soil moisture stresses at all growth stages severely affected shallot yield and quality. Frequent irrigation at 25% depletion of available moisture throughout the growing season was required to achieve high yields. However, frequent irrigation was also found to reduce the quality and storability of the bulbs.

Nitrogen fertilization promoted vegetative growth, delayed bulb development and exposed plants to soil moisture stresses ahead of maturity and, thus, reduced yield of rain-fed shallots. When supplemental irrigation was provided, however, yield increases of about 10-15% from nitrogen fertilization in the range 75-150 kg ha^{-1} were achieved. The different nitrogen sources caused few and small differences in internal and external bulb quality. On the other hand, there were more storage losses in nitrogen-fertilized shallots.

Phosphorus fertilization at rates of 25 or 50 kg ha^{-1} increased yield and bulb weight even when soil analysis did not show deficiency. On the other hand, potassium was not found to be a limiting nutrient in the clay soil used in this study.

The potential for shallot yield improvements through irrigation and nitrogen fertilization needs consideration of better storage facilities. The advantages gained would otherwise be lost within few weeks after harvest as both conditions may increase storage losses and reduce bulb quality. Assessment of cultivars with better storability would also deserve further assessment.

Key words: Cultivar, Eastern Ethiopia, fertilizer, growth, irrigation, mulch, nitrogen, phosphorus, potassium, quality, rain-fed, shallots, stress, storage, yield.

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Contents

Appendix

Papers I-V

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Woldetsadik, K., Gertsson, U. & Ascard, J. Response of shallots to mulching and nitrogen fertilization. *HortScience* (in press).

II. Woldetsadik, K., Gertsson, U. & Ascard, J. 2002. Season, and nitrogen source and rate affect development and yield of shallot. *Journal of Vegetable Crop Production* 8, 71-81.

III. Woldetsadik, K., Gertsson, U. & Ascard, J. Response of shallots to nitrogen, phosphorus and potassium fertilizer rates. Submitted.

IV. Woldetsadik, K., Gertsson, U. & Ascard, J. Yield, quality and storability of shallots as affected by irrigation and nitrogen fertilization. Submitted.

V. Woldetsadik, K., Gertsson, U. & Ascard, J. Response of shallots to moisture stresses in Ethiopia. Submitted.

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Introduction

The shallot crop

Shallots (*Allium cepa* var *ascalonicum* Barker; syn. *A. ascalonicum* auct. non L.) are important alliaceous crops cultivated in many tropical countries as a substitute for bulb onions (*Allium cepa* L. var *cepa*). Although bulb onions can be grown in the tropics, farmers in tropical countries prefer shallots for their ability to propagate vegetatively. Shallots are also preferred for their shorter growth cycle, better tolerance to disease and drought stresses and longer storage life than the common onion and for their distinct flavour that persists after cooking (Currah & Proctor, 1990; Brewster, 1990; Grubben, 1994; Pathak, 1994; Sumiati, 1994; Abbey *et al*., 1998).

Apart from minor morphological differences, bulb onions and shallots have similarities in physiological processes, in cytology and at molecular levels (Currah & Proctor, 1990; Brewster, 1994; Arifin & Okubo, 1996; Le Thierry d'Ennequin *et al*., 1997; Krontal *et al*., 1998, 2000). Moreover, the growth requirements of shallots are about the same as those of most other species of Allium (Jones & Mann, 1963; Currah & Proctor, 1990; Brewster, 1994).

The common onion has large bulbs and the plants reproduce from seed. While a single bulb is a desired characteristic for the common onion, shallot plants normally produce clusters of several bulb splits (Figure 1) that number from 2 to 20 or more pieces, with an ideal marketable size of about 30-40 mm in diameter (Jones & Mann, 1963; Currah & Proctor, 1990; Brewster, 1994; Krontal *et al*., 2000). In tropical regions, some shallot genotypes rarely flower and even where seed production is possible, the majority of shallot genotypes are clonally propagated (Jones & Mann, 1963; Currah & Proctor, 1990; Messiaen *et al*., 1994).

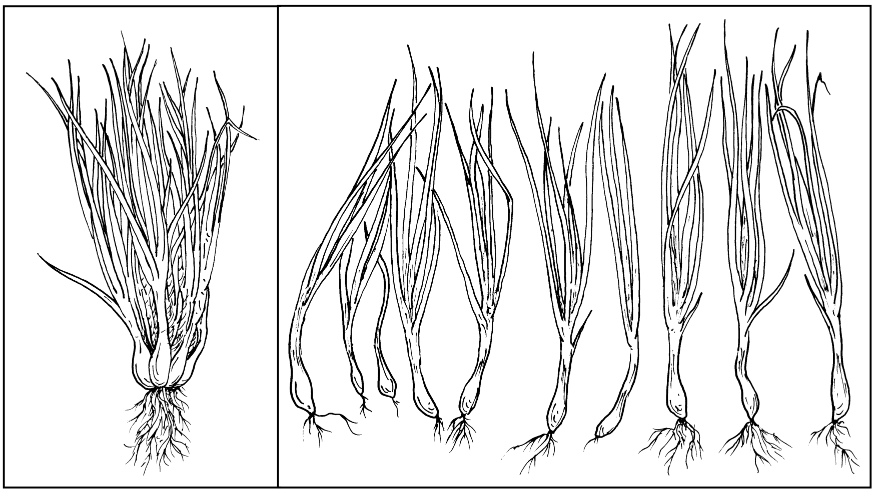

Fig. 1. A sketch of bulb cluster (left) and bulb splits (right) of a mature shallot plant (Sketch by Kim Gutekunst).

Soil moisture requirements of onions and shallots

Members of the onion family have an inefficient rooting system, making moisture management a key factor in production. They require a constant supply of moisture throughout the growing season (Currah & Proctor, 1990; Brewster, 1994). Greenwood *et al*. (1982) showed that 90% of the root system of the onion plant was concentrated in the top 40 cm of soil and that only 2-3% of the total root length was recorded below 60 cm depth, which indicates that very little water could be extracted from soil depths below 60 cm. Onion roots are mostly non-branching and all roots originate at the basal plate of the plant. Soil moisture is important in the growth of new roots and must reach the base of the bulb periodically if the newly formed roots from the stem are to grow into the soil (de Lis *et al*., 1967; Abdul-Jabbar *et al*., 1983; Brewster, 1994).

Soil water deficits inhibit leaf expansion, which reduces the amount of solar radiation intercepted as well as uptake of nutrients, because of reduced transpiration rates (Russell *et al*., 1989; Pereira & Chaves, 1993; Marschner, 1995). In onions, rates of transpiration, photosynthesis and growth are lowered by mild water stresses (El-Habbasha & Shaheen, 1976; Begum *et al*., 1990). Stressed onion plants may bulb too early, produce small-sized bulbs and bulb splits and, thus, produce reduced marketable yields (Hegde, 1986c, 1988; Brewster & Butler, 1989; Begum *et al*., 1990).

The soil moisture requirement of onions is influenced by several factors such as crop variety, soil type and physiological and environmental factors. A crop can be grown to maturity under a soil moisture deficit, but higher yields are generally associated with high irrigation frequencies, which avoid any water stress particularly at the time of bulbing (de Lis *et al*., 1967; Abdul-Jabbar *et al*., 1983; Doorenbos & Kassam, 1986; Hegde, 1988; Chung, 1989; Koriem *et al*., 1994; Shock *et al*., 1998; Suojala *et al*., 1998; Al-Jamal *et al*., 2000). Doorenbos & Kassam (1986) reported that the water requirement for onion yields of 35-45 t ha^{-1} could be attained with 350-550 mm of water using furrow irrigation. Ells *et al*. (1993) reported that furrow-irrigated onions required 1040 mm of water to obtain a yield of 59 t ha^{-1}. In furrow-irrigated onions in Oregon, USA, Shock *et al*. (1998, 2000a), showed that total yields and profits increased with irrigation threshold of soil water potentials between -17 kPa to -12.5 kPa at 20 cm soil depth under warm and dry growing conditions, while a lower irrigation threshold (-27 kPa) was required to maximize marketable yield and profits under cooler and wetter conditions. To maintain an irrigation threshold higher than -12.5 kPa, a highly efficient irrigation system, such as drip irrigation, is required (Shock *et al*., 1998).

Using a sprinkler system on sandy soils in Botswana, Imtiyaz *et al*. (2000) found that a fixed amount of 18 mm of irrigation applied at a cumulative class A pan evaporation of 11-22 mm was required to obtain the highest marketable yield of between 49 and 57 t ha^{-1}. Al-Jamal *et al*. (2001) in New Mexico observed that on sandy loam soils a sprinkler system, in which water applied to the field was limited to the amount needed to replace the evapotranspiration requirements of the onions, was better in water use efficiency than the trickle and furrow system. However, higher yields were achievable using a drip system compared to a sprinkler system (Al-Jamal *et al*., 2000). On the other hand, Ellis *et al*. (1986) did not find significant differences between furrow, sprinkler and drip irrigation systems on yields of onion grown on heavy textured soil in Colorado, USA.

De Santa Olalla *et al*. (1994) reported highest bulb yields of 64 and 74 t ha^{-1} in Spain from applying water at 100 or 120% crop evapotranspiration, respectively; and that 315- 415 mm of water provided over 17- 20 applications was needed in total. With a subsurface drip irrigation practice, Feibert *et al*. (1996) reported that onions required 1020 mm of water for a yield of 110 t ha^{-1}. Maintaining soil matric potential at high levels (higher than -20 kPa) by drip irrigation until shortly before harvesting was shown by Shock *et al*. (2000b) in Oregon, USA, to increase bulb size and yield of onions with little effect on storability of the bulbs.

In arid and semi-arid regions, water availability is generally the most important factor for onion production. Cultivation of crops without sufficient rainfall or irrigation demands efficient ways of utilizing any water reserves available to the plant. Mulching with plant residues and synthetic materials is a well-established technique for increasing the profitability of many horticultural crops (Ashworth & Harrison, 1983; Carter & Johnson, 1988; Duranti & Cuocolo, 1989). Different kinds of mulching materials under different soil and climatic conditions are shown to increase plant growth and yields and improve bulb size of onions. Such effects are mainly attributed to the capacity of the mulch to conserve soil moisture (Abdel, 1990; Adetunji, 1994; Abu-Awwad, 1999; Shock *et al*., 1999; Vavrina & Roka, 2000).

In a semi-arid region of Nigeria, Adetunji (1994) compared soil mulches of transparent polyethylene, millet stover and groundnut shell in an irrigated onion field and found yield increases of 80, 50 and 44%, respectively, compared with a bare soil yield of 4.5 t ha^{-1}. He also observed that the soil mulches maintained a higher soil water potential of between -10 and -30 kPa than bare soil (-75 kPa) during the irrigation cycles. In a greenhouse pot experiment, Abu-Awwad (1999) found that mulching the soil surface reduced the amount of irrigation water needed by 70% compared with the open soil surface at similar onion yields.

While reports on shallot irrigation and soil moisture management are limited, the crop may suffer from water stress and consequently reduced yields (Leong, 1986; Grubben, 1994; Abbey & Fordham, 1997, 1998). In pot-grown shallot plants, Leong (1986) observed that a daily 12.5 mm application of water gave better yields than application of the same or lower amounts at longer intervals.

Nutrient requirements of onions and shallots

Nitrogen, phosphorus and potassium are often referred to as the primary macronutrients because of the general probability of plants being deficient in these nutrients and because of the large quantities taken up from the soil relative to other essential nutrients (Marschner, 1995). Onions are more susceptible than most crop plants in extracting nutrients, especially the immobile types, because of their shallow and unbranched root system; hence, they require and often respond well to additional fertilizers (Brewster, 1994). Shallots are considered to have similar nutritional requirements to other Alliums (Currah & Proctor, 1990; Brewster, 1994; Zahara *et al*., 1994).

Nitrogen

Nitrogen (N) is required in much greater quantities than most other nutrients. Nitrogen is an important component of proteins, enzymes and vitamins in plants, and is a central part of the essential photosynthetic molecule, chlorophyll (Marschner, 1995). Plant demand for N can be satisfied from a combination of soil and fertilizer N to ensure optimum growth.

The major source of plant-available N in soil is mostly the N mineralised from soil organic matter and fresh crop residues. The rate of these processes is dependent on soil temperature and soil moisture content (Parton *et al*., 1987; Marschner, 1995). Soil mineral N levels can vary widely from field to field and over time. In a series of 27 field experiments on vegetable growing soils located throughout the UK, measurements of soil mineral N varied from 40 to over 300 kg N ha^{-1} (Greenwood *et al*., 1992). It is also important to ensure that mineralised N is available within the rooting zone of onion plants, particularly during the early stages of growth (Brewster, 1994; Rahn *et al*., 1996).

Accounting for soil N and expected release from the soil, additional N application may be necessary in order to meet the crop N requirements. The amount of nitrogen needed is usually based on soil organic matter content, crop uptake and yield levels. Nitrogen uptake levels by onion crops may vary from less than 50 kg to more than 300 kg ha^{-1}, depending on cultivar, climate, plant density, fertilization and yield levels (Hegde, 1986a, 1988; Sørensen, 1996; Suojala *et al*., 1998; Salo, 1999; Pire *et al*., 2001).

Under sub-optimal supply of N, onions and shallots can be severely stunted, with bulb size and marketable yields reduced. By contrast, too much nitrogen can result in excessive vegetative growth, delayed maturity, increased susceptibility to diseases, increased double centres in onions, reduced dry matter contents and storability and, thus, result in reduced yield and quality of marketable bulbs (Riekels, 1977; Brewster & Butler, 1989; Singh & Dankhar, 1991; Batal *et al*., 1994; Brewster, 1994; Ruaysoongnern & Midmore, 1994; Henriksen & Hansen, 2001; Sørensen & Grevsen, 2001).

The amount of N applied and onion crop responses vary from place to place. High yielding varieties usually require more nitrogen than low yielding. Results from different climatic regions of the world also show varying responses of onions to applied nitrogen. For example, onion yields were increased when applied N rates were in the range 0-50 kg ha^{-1} in the northwest region of Australia (Laughlin, 1989). In semi-arid South Texas without irrigation, Wiedenfeld (1994) found no additional yield benefit from applying N rates higher than 84 kg ha^{-1} and average N uptake efficiency less than 10% using different application times and rates.

On irrigated silty clay soil with a high level of residual NO3-N in Arkansas, USA, Halvorson *et al*. (2002) observed a 27% increase in fresh bulb yield from N fertilization of 224 kg ha^{-1}. On a sandy loam soil in a semi-arid region of Ethiopia, irrigated onion plants benefited from application of 90-120 kg ha^{-1} N compared to unfertilised crops (Aklilu, 1997). On a tropical Ultisol in Nigeria, Asiegbu (1989) found onion yield increases from applying N up to 150 kg ha^{-1}. In other studies, increased onion yields were obtained from N fertilization of 143-246 kg ha^{-1} on loamy soils in Egypt (Haggag *et al*., 1986); 200 kg ha^{-1} on sandy soils in Saudi Arabia (Al-Moshileh, 2001); and 299-358 kg ha^{-1} on siliceous sands in Australia (Maier *et al*., 1990). The efficacy and utilisation of N by onion crops were also shown to be correlated with the availability of soil moisture (Hegde, 1986a, 1988; Greenwood *et al*., 1992; Wiedenfeld, 1994; Rahn *et al*., 1996).

It has also been shown that N source, nitrate or ammonium forms, may influence vegetative growth, yield and quality of onions (Batal, 1991; Gamiely *et al*., 1991; Batal *et al*., 1994; Drost *et al*., 2002). Gamiely *et al*. (1991) reported that nitrate alone or in combination with ammonium-N increased plant growth and bulb dry weight compared to ammonium-N as the sole nitrogen source. Batal *et al*. (1994) observed ammonium nitrate to be superior to calcium nitrate or sodium nitrate in producing jumbo and large size onions; however, he also found ammonium nitrate to cause a higher rate of bulb decay than the other N sources.

Efficient nitrogen fertilization should consider the risk of leaching losses of nitrate and possible damage to the environment (Neeteson *et al*., 1999). Large quantities of N fertilizers may be required to obtain high yields of quality onion bulbs, but large amounts of N may also remain in the soil after harvest. In the Netherlands, de Visser (1998) estimated that about 50% of the 100-120 kg ha^{-1} N commonly applied to onion fields was leached out of the soil. In Japan, Hayashi & Hatano (1999) also calculated that the N leached annually from an onion field could correspond to 58% of applied N. Hence, assessment of the right amount and time of application are essential in reducing the risk of nutrient losses.

Phosphorus

Phosphorus (P) deficiency is one of the largest constraints to crop production in many tropical soils, owing to low native content and high P fixation capacity of the soil (Warren, 1992; Barber, 1995; Marschner, 1995; Norman *et al*., 1995; Fairhust *et al*., 1999). Accordingly, P fertilization is usually recommended in these regions. Phosphorus is essential for root development and when the availability is limited, plant growth is usually reduced. The movement of P in soils is very low and its uptake generally depends on the concentration gradient and diffusion in the soil near roots (Marschner, 1995; McPharlin & Robertson, 1999).

In onions, P deficiencies reduce root and leaf growth, bulb size and yield and can also delay maturation (Ojala *et al*., 1983; Brewster, 1994; Greenwood *et al*., 2001). In soils that are moderately low in P, onion growth and yield can be enhanced by applied P. Results of long-term fertilizer trials on loamy sand soils in Germany have shown a strong response of onions to P fertilization in the range 0-52 kg ha^{-1} P (Alt *et al*., 1999). Depending on yield levels, P uptake rates in onion are estimated to be about 15-30 kg ha^{-1} (Hegde, 1988; Alt *et al*., 1999; Pire *et al*., 2001; Salo *et al*., 2002). For a yield of 6.6 t ha^{-1} shallots grown on peat soil in Malaysia, Vimala & Yeong (1994) estimated P uptake of about 5 kg ha^{-1}.

Depending on soil P status, cultivar and plant density, P application rates of up to 200 kg ha^{-1} were found to maximize onion yields and bulb weights (Haggag *et al.*, 1986; Vachhani & Patel, 1993; McPharlin & Robertson, 1999; El-Rehim, 2000; Singh & Singh, 2000; Singh *et al.*, 2000) and reduce storage loss of bulbs (Singh *et al.*, 1998). Increased P levels are also known to improve bulb size and the number of marketable bulbs in shallots (Zahara *et al.*, 1994; Nagaraju *et al.*, 2000). Regardless of the P status of the soil, placement of P-fertilizers in the soil near to the plant would be the most effective method of P supply to onion plants (Mulkey *et al.*, 1979; Brewster, 1994; Henriksen & Hansen, 2001).

Potassium

Onions take up potassium (K) in quantities nearly equivalent to N (Haggag *et al.*, 1986; Hegde, 1988; Pire *et al.*, 2001; Singh & Verma, 2001; Salo *et al.*, 2002). Moreover, like N, K is easily leached from soils and fertilization may be needed for high yields (Brewster, 1994; Marschner, 1995). The K requirement of onion plants increases with yield and its functions are linked to photosynthesis (Marschner, 1995; Greenwood & Stone, 1998). If K is deficient or not supplied in adequate amounts, onion plants can be stunted, become susceptible to disease and have reduced yields (Develash & Sugha, 1997; Rizk, 1997; Singh & Verma, 2001). Yield responses of onions to applied K would be less likely on soils with high cation exchange capacity such as certain types of clay soils (Marschner, 1995), low soil moisture contents (Kuchenbuch *et al.*, 1989; Al-Moshileh, 2001) and low yielding cultivars (Boyhan & Hill, 2001).

Background and objectives of the study

Background

Shallots and onions are among the most important vegetables in Ethiopia. The total area under production of shallots and onions in Ethiopia is estimated at 10,000 ha, with average yields of about 7.5 t ha^{-1} (Aklilu, 1997). Shallots in particular are widely cultivated as a source of income by peasant farmers in many parts of the country. They have a wide range of climatic and soil adaptation and are cultivated both under rain-fed and irrigated conditions. They are grown primarily for the bulb, although the green tops may also be consumed. In Ethiopia, shallots and onions are used for flavouring the local stew, ‘wot’ and are used in many households almost daily.

Eastern Ethiopia has a privileged position for cash crop production and marketing, with the trading potential exceeding the actual production capacity (Storck *et al.*, 1991). However, variability of rainfall from year to year and uneven distribution during the growing seasons cause a wide range of climatic hazards for farmers. Moreover, increasing population density coupled with lack of alternative employment opportunities has led to a progressive land pressure and subsequent shrinking of individual landholdings to where about 82% of farmers have less than or equal to one hectare (Adenew, 1992; Emana, 1992). As a result, arable land must be used intensively, leaving practically no room for fallowing.

In eastern Ethiopia, there are two crop production seasons, which follow a bimodal rain distribution: small rains from March to May and long and heavy rains from June to September (Figure 2). Shallots are grown in the mid- and low altitude areas under rain-fed conditions and to some extent under irrigation. They are generally cultivated in pure stands and when rain-fed, farmers prefer the drier small rainy season or delayed planting in the main rainy season in order to lower incidence of diseases.

Moreover, there is a belief among growers that too much rain or irrigation will result in excessive lateral branching and increased proportions of small unmarketable bulbs, thus limiting them to a practice of cultivation under low soil moisture periods, although farmers are fully aware of the problem. As a result, crops are usually moisture-stressed and yields are commonly very low. On the other hand, farmers need to increase yields of their cash crops, which they use for purchasing cereals from neighbouring surplus-producing regions. Whenever available, growers use farmyard manure as well as nitrogen fertilizer to increase yields. However, no data are available to substantiate the belief that benefits can be obtained from fertilization of shallots, especially under low soil moisture conditions.

Therefore, a better understanding of the moisture and nutrient requirements of shallots is needed in order to develop management strategies, which optimise moisture and fertilizer use of the crop and thereby increase returns to producers. Moreover, improved moisture and fertilizer management for shallots may help to improve quality, particularly bulb size and storability, and thus offer growers premium prices.

The hypothesis was that in a sub-humid tropical climate with soils of average fertility, soil moisture conservation and irrigation practices could ensure high yields of shallots even at low levels of fertilization; and that it would be less likely to obtain benefits from fertilization under low soil moisture conditions. It was assumed that shallot cultivars would vary in their responses to irrigation and fertilization levels and that sources of fertilizer would affect the response of shallots to nitrogen fertilization. Furthermore, it was assumed that lateral branching would be associated more with cultivar characteristics than with soil moisture and soil fertility levels.

Objectives

The study was conducted with the following objectives:

- to assess yield and quality of shallots under mulching and nitrogen fertilization,
- to assess growth, yield and quality of shallots under varying levels of nitrogen, phosphorus and potassium fertilizations,

- to evaluate the effect of different nitrogen fertilizer sources on yield of shallots,
- to assess the impact of soil moisture stress and irrigation regimes on growth, yield and quality of shallots,
- to evaluate responses of two shallot cultivars, local and improved, to nitrogen fertilization and irrigation,
- to find out whether high soil moisture and soil fertility could alter the development of lateral branching in shallots and affect marketable bulb yield and quality.

Materials and Methods

Location

Field experiments were conducted at Alemaya University, Ethiopia (42°3' E 9°26' N), about 530 km east of the capital, Addis Ababa. The experimental area is characterized as sub-humid type tropical climate with average annual rainfall of about 790 mm (average for 1979-1997) with variations between 573 and 1017mm. During the study period (1998-2001) mean annual rainfall was 775 mm, but the distribution showed wide variation from the long-term mean. Mean monthly distribution of rainfall in the long-term and during the experimental period are shown in Figure 2. The rainfall has a bi-modal distribution pattern with small rains from March to May and long and heavy rains from June to September. The mean annual temperature of the experimental site is about 17 ºC (1979-2001) with ranges of 18-20 ºC during the short rainy and 14-18 ºC during the main rainy seasons. The experimental soil was a heavy clay (about 50% clay), representing the major shallot-growing soil in the area, and had low to moderate organic matter content (2.3-4.6%).

Plant material

Shallot cultivars used in this study included two selections (improved varieties) 'DZ-Sht-78' and 'DZ-Sht-91' and one farmers' cultivar, 'Fedis'. The cultivar 'DZ-Sht-78' was used in two experiments (Papers I and V), the cultivar 'DZ-Sht-91' in three experiments (Papers II-IV) and the cultivar 'Fedis' in one experiment (Paper IV). The improved cultivars were recent selections by Debre Zeit Agricultural Research Centre, Ethiopia, from local landraces on the basis of yield merits under intensive management practices (Debre Zeit Agricultural Research Centre, personal communication). The farmers' cultivar 'Fedis', which is mainly cultivated as rain-fed under less intensive farming systems in eastern Ethiopia, was included for comparison of responses to fertilization and irrigation. For all experiments, the planting materials were propagated and maintained vegetatively under uniform conditions at the experimental site.

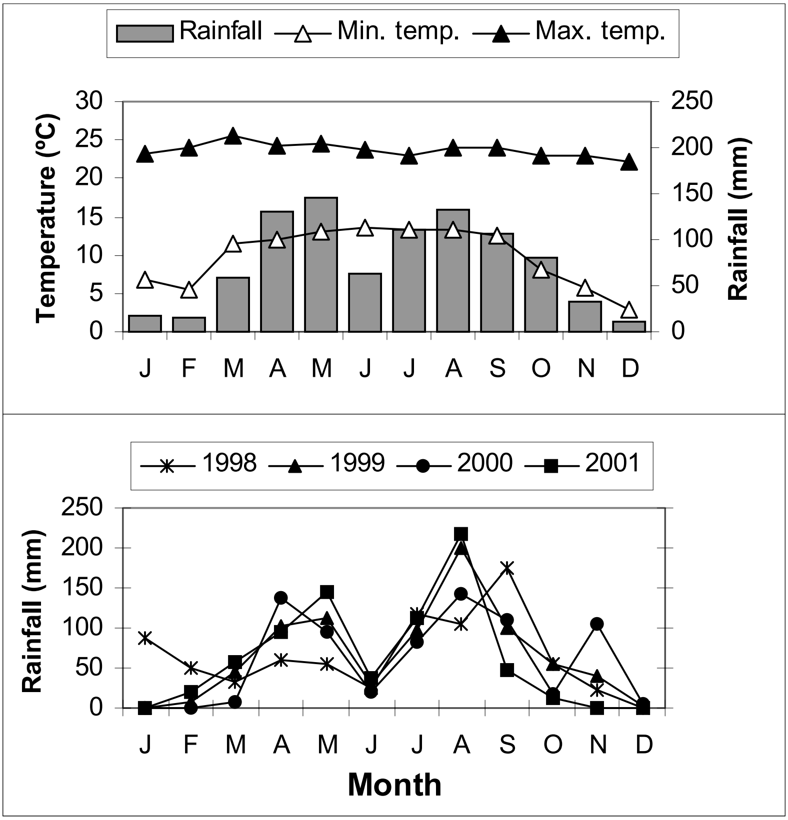

Fig. 2. Monthly mean rainfall and minimum and maximum temperatures for the period 1979-1997 (top) and rainfall distribution during the study period (bottom).

Methods

Four series of field experiments, each repeated two or three times, were carried out under rain-fed conditions or with supplemental irrigation, and dry season irrigated crops during the period 1999-2002 (Table 1). One study (Paper V) was conducted once in a glasshouse and once in the field. Planting time for rain-fed experiments followed farmers' practices of small rainy season crop (primary crop) in April and main rainy season crop (secondary crop) in August or September. Irrigated crops were grown during the drier months of the year. A summary of experiment types and growing seasons is shown in Table 1.

Plots for each experiment were selected from a piece of land under maize cultivation in the preceding year. Land preparation, planting and crop management followed local practices and were uniformly applied to all treatments. Data on plant growth, yield, quality and associated parameters were collected and analysed as described under each experiment (Papers I-V).

Table 1. *Summary number of experiment and crop growing periods*

Experiment	Crop season		
	Short rainy season	Main rainy season	Irrigated dry season
Paper I	1999	1999	-
Paper II	2000[z]	1999, 2000 [z]	-
Paper III	-	1999, 2001 [z]	2000
Paper IV	-	-	1999, 2001, 2002
Paper V	-	-	1999 [y], 2000

[z] = supplemental irrigation provided.
[y] = glasshouse experiment

Results and Discussion

Mulching

The mulching experiment (Paper I) was conducted for two seasons with the objectives of determining how different mulching materials affect growth, yield and quality of shallots and of determining nitrogen fertilizer utilization under different mulches.

Black plastic mulch increased shallot yield three-fold in the short season and by one fourth in the main season compared to the bare ground treatment. This result is in agreement with previous reports on the beneficial effects of black polyethylene through its effective weed control, conservation of soil moisture and increasing soil temperatures (Bonanno & Lamont, 1987; Adetunji, 1994; Chhangani, 2000; Vavrina & Roka, 2000; Rahman & Khan, 2001). The straw and clear plastic mulches increased yield during the short season, but slightly reduced yield in the main season. High weed infestation appeared to be the main reason for reduced yield in the latter season.

Leaf numbers and plant height had a linear correlation with the availability of soil moisture, the effect of which was reflected in bulb weight and yield. El-Habbasha & Shaheen (1976), Talha *et al*. (1978) and Begum *et al*. (1990) also reported similar relationships for onions. The soil moisture conservation efficiency of the straw mulch was equivalent to, or better than, that of the black plastic mulch. However, its effect on yield was inferior to that of black plastic, partly because of lower soil temperature and reduced nutrient availability. Heavy weed infestation and reduced soil moisture in clear plastic mulched plots were reasons for its lower efficiency compared to the black plastic mulch. There was no need for addition of nitrogen fertilizer in any of the mulch treatments.

Fertilisation

Nitrogen source and rate

Responses of shallot plants to nitrogen fertilizer rates were evaluated under different growing conditions and seasons. In the first experiment (Paper I), rates were studied in combination with different mulches during the main and short rainy seasons. In the second experiment (Paper II), nitrogen rates from different fertilizer sources were assessed with rain-fed and irrigation-supplemented crops. The third experiment (Paper III) dealt with nitrogen rates with phosphorus and potassium fertilizers both in rain-fed and in irrigation-supplemented crops. The fourth experiment (Paper IV) investigated nitrogen rates with different irrigation regimes.

There were few apparent differences between the N fertilizer sources in most of the plant and bulb parameters studied (Paper II). However, ammonium nitrate and urea gave relatively better yields than ammonium sulphate.

Results summarized in Table 2 show that nitrogen fertilization could reduce yield of rain-fed shallots. Both in the main and in the short rain seasons, soil moisture contents were found to be low during peaks of the growing periods. With increased N rates, shallot plants tended to have more vegetative growth, delayed maturity and reduced bulblet sizes. When crops received supplemental irrigation, however, more marketable bulbs per plant were obtained with increased rates of N, which in turn raised yields up to fertilization rates of 150 kg ha^{-1} N (Papers II and III). Results of these studies were in agreement with previous reports that showed N utilisation in the onion crop to be correlated with the availability of soil moisture (Hegde, 1986a, 1988; Begum *et al*., 1990; Greenwood *et al*., 1992; Thabet *et al*., 1994; Wiedenfeld, 1994; Rahn *et al*., 1996).

Table 2. *Summary of yields of shallots fertilized with varying rates of nitrogen fertilizer during different cropping seasons*

Nitrogen rate (kg ha^{-1})	Paper I	Paper III			Paper III			Paper IV
	MS & SS	MS	SS+ Irrig^z	MS+ Irrig^y	MS	MS+ Irrig^y	SS+ Irrig^y	Irrigated
0	10.1	25.3	24.7	28.5	29.9	27.5	29.0	25.5
50	-	23.7	26.9	28.3	-	-	-	-
75	9.9	-	-	-	29.7	31.7	31.5	25.8
100	-	19.5	23.9	31.4	-	-	-	-
150	9.4	20.6	24.9	32.1	27.6	30.9	32.8	25.0
200	-	18.6	23.0	29.0	-	-	-	-
225	-	-	-	-	-	18.9	-	-
$P \leq 0.05$	NS	*	*	*	*	**	**	NS

MS, SS= Main rainy season and short rainy season, respectively.
^{z} = supplemental irrigation for establishment only.
^{y} = Supplemental irrigation provided when available soil moisture dropped to 40%.

On the other hand, the yields of irrigated shallot crops during dry and warm season were little affected by N fertilization. This could be attributed to the relatively high organic matter content of the soil and warmer growing season, which may have enhanced release and availability of N to plants (Cassman & Munns, 1980; Myrold, 1987; Marschner, 1995) compared to the rainy season crops. Moreover, the response of shallots to applied N during the rainy seasons with supplemental irrigation could be due to N loss by leaching and competition from higher weed populations compared to the dry season irrigated crops.

Increasing N rates did not significantly affect lateral branching in shallot (Table 3).but improved the dry matter, soluble solids and pungency of the bulbs in many of the experiments. However, improvement in these parameters may be of little significance for growers who are not selling their produce on a quality basis. Moreover, a higher risk of bulb storage losses was observed in N-fertilized plants. Riekels (1977), Singh & Dankhar (1991) and Batal *et al*. (1994) also showed that high levels of nitrogen fertilization promote sprouting and decay of onions. Hence, N fertilization practices by growers need reconsideration on the basis of soil fertility and moisture availability, growing season and the possibility of better storage facilities or immediate use of the bulbs.

Phosphorus

The effects of phosphorus fertilization on shallots were evaluated in three field experiments under rainfall and irrigation (Paper III). Treatments during the first two seasons included three P rates: 0, 25 and 50 kg ha^{-1}. During the third season, a fourth rate, 75 kg ha^{-1} P, was included. Both in the rain-fed and irrigated crops, P at the rates of 25 kg or 50 kg ha^{-1} increased yield and mean bulb weight of shallots even though the soil analysis did not show P deficiency. The positive responses of shallots to P fertilization were mainly due to the fact that the plants have too weak root systems to efficiently explore and utilize soil P and the high P fixation capacity of the soil used for this study (Mulkey *et al*., 1979; Greenwood *et al*., 1982, 2001; Brewster, 1994; Marschner, 1995). The results show that P should be applied to improve bulb size and yield of shallots. The dry matter, pyruvate and soluble solids contents and the storability of bulbs were not much affected by applied P.

Potassium

The response of shallots to potassium fertilization was assessed under rain-fed and irrigated conditions for two consecutive seasons (Paper III). Application of K did not show any clear effects on growth, yield or quality of shallots. The shallot bulb K content and uptake both from fertilized and unfertilised plots remained almost identical, indicating that K was not a limiting nutrient in the clay soil used for the experiment. Clay soils are known to be important sources of soil K and possess a better K-buffering capacity than other types of soils (Marschner, 1995).

Irrigation

This part of the study was conducted to evaluate yield, quality and storability of shallots under varying levels of irrigation and nitrogen fertilization (Paper IV). Two cultivars, farmers' local ('Fedis') and improved selection ('DZ-Sht-91') were used in the study.

Bulb yields were more improved when plants were irrigated at 75% available soil moisture (ASM) than at 50% or 25% ASM. However, irrigation water use efficiency was higher at the irrigation treatment of 50% ASM than at 25 or 75% ASM. The increase in bulb weight and number of marketable bulbs accounted for the yield increases in this experiment. Brewster (1990) and Shock *et al*. (1998) also showed that onion yields were affected when the available soil moisture in the surface topsoil dropped below 60-80%. Irrigation frequency did not significantly affect the number of lateral branches in either shallot cultivar (Table 3). On the other hand, the most frequent irrigation reduced the dry matter and pyruvate contents of bulbs, which has also been reported for onion (Hegde, 1986b; Chung, 1989; Randle, 1997).

Table 3. *Lateral shooting of shallots under different nitrogen fertilizer and irrigation regimes*

Nitrogen fertilizer ^{z}		Irrigation ^{y}	
Rate (kg ha^{-1})	Laterals per plant	at ASM^{x} (%)	Laterals per plant
0	6.7	75	6.8
75	6.6	50	7.4
150	6.5	25	7.7
$P \leq 0.05$	NS		NS

^{z} = average of six field observations.
^{y} = average of three field observations.
^{x} = available soil moisture.

The storage performances of the two cultivars showed differences due to the irrigation treatments. In the local 'Fedis' cultivar, the proportions of total weight loss and rotting losses were generally high and did not differ due to irrigation treatments, while in the improved 'DZ-sht-91' the losses in the 75% ASM treatment nearly doubled compared to that in the 25% ASM treatment. Of the total losses in 'Fedis', rotting amounted to about 44%, while in 'DZ-sht-91' it was about 26% after eight weeks of storage in the 75% ASM treatment. As a result, in 'DZ-sht-91', marketable bulb weight after eight weeks of storage did not differ due to the irrigation treatments, while in 'Fedis' the 75% and 50% ASM treatments had 20% and 30% more marketable weight, respectively, than the 25% ASM treatment. Galván *et al*. (1997) and Gamie *et al*. (2000) showed differential responses of onion cultivars to irrigation and storability. Higher irrigation has also been shown to increase susceptibility of onion bulbs to storage diseases (Chung, 1989; Hassan, 1996; Shock *et al*., 1998).

In general, the storability of shallots under ambient weather condition appeared to be very poor, due to moisture loss from the tissues and rotting of bulbs. Hence, shallot crops should be irrigated frequently only if they are to be sold soon after harvest or if alternative storage other than ambient conditions is available. Moreover, if water becomes a limiting factor, the 50% ASM irrigation level would be the most appropriate.

Soil moisture stress

Pot and field experiments were carried out to assess the impact of moisture stresses on growth and yield of shallots (Paper V). Plants received stress treatments (withholding watering up to 100% depletion of available moisture) at early, mid- and late growth stages (15-45, 46-75 and, 76-105 days after crop emergence, respectively).

Both in the pot- and field-grown shallots, withholding irrigation water to 100% depletion of available soil moisture at any stage of the growing period reduced growth and yield. The early and mid-growth stage stress treatments reduced bulb weight by about 20%, while late stage stress tended to increase it. Bulb yield was reduced by about 42 and 26% in the pot-grown plants and by 46 and 52% in the field-grown plants as a result of the early and mid-growth stage stresses.

Early stage water stress reduced the formation of lateral branches, while mid-stage stress affected both bulb numbers and bulb weights. In shallots raised from seed, Abbey & Fordham (1997) found no effect of water stress on the number of auxiliary shoots but they showed that adequate and regular watering at the seedling stage was required for the highest bulb weight and yield. In the present study, regular watering at 40% depletion of available soil moisture throughout the growing season was required to achieve the highest bulb yields, but withholding watering to 100% depletion at late season improved mean bulb weight without much effect on yield. Moreover, late stage stress appeared to increase the DM content of the bulbs.

In the eastern part of Ethiopia, where drought stress at any of the growth stages of a shallot crop is a common phenomenon, conservation of soil moisture and provision of supplemental irrigation are required during the early and mid-growth stages of the crop to improve bulb weight and yield of the crop.

Concluding Remarks

The results of the present experiments show the significance of soil moisture for shallot production in the sub-tropical climate. High soil moisture regimes, maintained through mulching and irrigation treatments, markedly increased the proportion of bulblets developing from the laterals to marketable sizes. The growers' notion that high soil moisture regimes encourage excessive lateral branching and reduce bulb size, thereby lowering marketability of the produce, was shown to be wrong. Given other growing conditions, the same soil moisture content did not alter the number of laterals formed in shallots propagated by bulb division.

Regarding the seasonal differences in shallot plant growth and yield, the main rainy season crops were found to be inferior to the short rainy season and dry season irrigated crops. The relatively cooler growing conditions in the main rainy season delayed the onset of bulbing and bulb enlargement and could have encouraged lateral growth. This and the disease problems appear to be the reasons for the low productivity of shallots in the main season. The growers' approach of delaying planting to avoid disease problems also risks soil moisture stress at the peak of bulb development, a fact that could result in very low yields. The small rainy season rainfall was not sufficient to exploit the yield potential of the shallot crop. Although moisture conservation treatments during this period proved to double yields, supplemental irrigation was required to further increase yields.

Yields of shallots exposed to soil moisture stresses at all growth stages were severely affected. Frequent irrigation at 25% depletion of available moisture throughout the growing season was required to achieve high yields. However, frequent irrigation may also reduce the quality and storability of the bulbs. In order to improve quality and storability, and when irrigation water becomes a limiting factor, irrigation at 50% depletion of available soil moisture would be most appropriate. Furthermore, watering could be withheld towards physiological maturity in order to improve storability and quality of the bulbs. Under such conditions, yield losses due to reduced soil moisture would be compensated for by water use efficiency and better storability.

The present work also indicated that under a sub-humid tropical climate with medium soil fertility, rain-fed shallots should not be fertilized with N unless the crop growth period can be extended by supplemental irrigation. Nitrogen fertilization was found to promote vegetative growth, delay bulb development and expose plants to soil moisture stresses ahead of maturity in rain-fed crops. When irrigated, shallot yields were increased by about 10-15% by N fertilization in the range 75-150 kg ha^{-1}. The results also demonstrated that there was no yield difference in shallots fertilized with different N sources indicating that there is no need for substitution of Urea, the most commonly used N fertilizer in Ethiopia.

Under relatively higher soil organic matter contents and warm and moist growing conditions yield responses to applied N were little affected. Rather, bulbs from N fertilized crops suffered losses in storage due to enhanced sprouting. Slight increases in bulb dry matter contents and pungency were achieved by N fertilization, but these may have little relevance.

The use of phosphorus both in rain-fed and irrigated crops was found to improve bulb size and yield without affecting internal quality of the bulbs. Although soil tests might not show critical P status, applications in the range 25-50 kg ha^{-1} may be required for yield targets of about 30-35 t ha^{-1}. On the other hand, the present work showed that potassium fertilization of shallots was not required on the clay soil where the experiments were carried out.

The maximum shallot yield observed in this study was about 37 ton ha^{-1} with the improved cultivar ("DZ-Sht-91") under ample soil moisture (irrigated at 25% depletion of soil moisture) and by applying 150 kg N ha^{-1} and 25 kg P ha^{-1}.

In summary, yields of shallots could be improved substantially through soil moisture conservation and irrigation in the sub-humid tropical climate. Fertilizer recommendations, especially nitrogen, require consideration of the availability of soil moisture and the growing season in addition to the fertility status of the soil. The potential for yield improvements through irrigation and nitrogen fertilization, however, needs consideration of better storage facilities or immediate use of the bulbs as both conditions increase storage losses and the advantages gained would be lost within few weeks after harvest. The differential response between cultivars to irrigation hints at possibilities for getting cultivars with better storability and thus deserves further assessment.

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