Fertigation Proceedings: Selected Papers
of the IPI-NATESC-CAU-CAAS
International Symposium on Fertigation
Beijing/China, 20-24 September 2005

Fertigation:

Optimizing the Utilization of Water and Nutrients

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Edited by: Dr. Patricia Imas
IPI Technical Secretariat
ICL Fertilizers
Potash House, P.O. Box 75
Beer Sheva 84100, Israel

M. Ron Price
15, Rav'on St.
Giv'at Savion 55900, Israel

International Potash Institute
P.O. Box 569
CH-8810 Horgen
Switzerland

Baumgärtlistrasse 17
P.O. Box 569
CH-8810 Horgen, Switzerland
Tel.: +41 43 810 49 22
Fax: +41 43 810 49 25
E-mail: ipi@ipipotash.org
www.ipipotash.org

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Foreword

The International Symposium on Fertigation under the theme "Optimizing the Utilization of Water and Nutrients" was held in Beijing, 20-24 September 2005, Beijing Conference Center.

Fertigation receives a great deal of interest in China because of the potential to save water and nutrients, while at the same time, increase agricultural productivity. In the late 1990s, the Chinese National Agro-technical Extension and Service Centre (NATESC) and the International Potash Institute (IPI) responded to this need by initiating a series of activities at farm and extension level to demonstrate the benefits of fertigation through publications, field experiments, training courses and famers' days. These efforts are yielding a wide acceptance of fertigation by scientists, extension officers and policy makers in China.

Jointly organized by IPI and NATESC, and assisted by the Chinese Agriculture University (CAU) and the Chinese Academy of Agricultural Sciences (CAAS), the symposium presented the first international meeting fully dedicated to the topic of fertigation to be conducted in China.

The use of fertigation with micro-irrigation systems is one of the critical measures required to meet the mounting demands on water resources and the acute need for the efficient use of nutrients in China. Yet, development of fertigation is dependent on government policy to assist in the required financial investment, on industry to supply competitive solutions of technology and fertilizers, and above all, on farmers' deep understanding and knowledge of how to apply this technique to various crops growing in different agro-climatic zones.

The papers in these proceedings demonstrate the many uses of fertigation and highlight the opportunities created by effectively managing water and nutrients. We hope that the proceedings provide a modest contribution to enhancing knowledge for the development of fertigation in China, and can be drawn on to improve water and nutrient use efficiency in Chinese agriculture.

Hillel Magen
Director, IPI

Tian Youguo
Division Chief, NATESC

Preface

Irrigation is a crucial component in the production of food crops. While various types of flood irrigation have been practiced for thousands of years, water scarcity in more recent years has stretched the innovative nature of man and since the early years of the 60s trickle and other micro-irrigation systems have been rapidly developed. Now at the onset of the 21^{st} century, the growing demand on water resources by the agricultural, urban and industrial sectors is, creating even more opportunities for the use of advanced irrigation technologies.

Fertigation - the incorporation of soluble fertilizers into irrigation lines enabled - for the first time - harmonization and integration between the application of water and plant nutrients. This was a natural development to meet the requirement of limited root zone development with micro-irrigation systems. Fertigation also enables the productive use of saline and marginal soils, sand dunes and mountain slopes bringing them into agriculturally productive soils; it also enables efficient use of nutrients, saving of labor, reduction of weed growth and herbicide usage as well as the use of low quality water.

The tremendous potential of fertigation in saving water and fertilizers without compromising the yield and the quality of food and fibre crops, along with the reduction of nutrient losses to the environment makes it an attractive system to which governments should consider assisting farmers in their initial investment requirements. The flexibility of this technique enables its use in small scale farming as well as in large industrial field crops and plantation production systems.

The papers in these proceedings describe various issues relating to fertigation in different cropping systems and agro environments. These data can be used as a starting point for the expansion of scientific knowledge and the practical use of fertigation, to meet more and more site specific needs and demands arising from water scarcity and ecological intensification of crop production and the resources needed. The 16 papers presented in these proceedings demonstrate the introduction of intensive field and theoretical efforts of very high scientific knowledge in solving a wide range of practical problems. These studies are wide ranging covering agricultural and horticultural production from vegetable to orchard crops and hydroponics as well as the interactions of nutrients with salinity in plant development.

It is my hope that this symposium and its proceedings will serve as a significant step in the development and dissemination of fertigation in the fast growing agriculture of China. Using this technology, scientists, extension officers and farmers have provision for a stable and sustainable production of food for all.

Uzi Kafkafi
Faculty of Agriculture
The Hebrew University of Jerusalem

Global Aspects of Fertigation Usage

Uzi Kafkafi

Department of Field Crops, Faculty of Agricultural, Food & Environmental Quality Sciences, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel. E-mail: kafkafi@agri.huji.ac.il.

Abstract

Shortage of water for desert agriculture was the first stimulus for the development of drip irrigation in Israel in 1960. Incorporation of fertilizers and clogging problem led to the development of the second generation of drippers, which featured turbulent flow. Within 40 years the principle of delivering water and nutrients to a specific zone near the plant roots has spread all over the world, and is now applied to greenhouses, row crops, vegetables and plantations. Computer-controlled irrigation and fertilization led to savings in labor costs and to accurate timing of irrigation. The flexibility of the fertigation system, at all scales from the individual small farmer using gravity driven irrigation to huge plantations and field areas, is one aspect that has quickly led to world-wide acceptance. The shortage of irrigation water worldwide is another factor that drives the expansion of fertigation, as well as the ability to safely use recycled sewage water for agriculture.

Keywords: crops, development steps, global expansion, nutrients supply rate, N form, subsurface drip irrigation.

Introduction

An old proverb says: “Necessity is the mother of all inventions”.

Subsurface trickle irrigation using a system of canvas tubes was tried by Robey (1934). In Israel, where water scarcity was the main stimulus, adoption of drip irrigation started from zero in 1960 and reached 6,000 ha by 1974; practical acceptance proceeded faster than research (Ravitz and Hillel, 1974). Flood and canal irrigation methods date back thousands of years in Egypt, Mesopotamia, India and China, and are still in use. Irrigation of small plots with water carried by hand in buckets is still practiced in many countries.

The worldwide irrigated areas are presented as percentages of the total land area in a map produced by the FAO (Siebert et al., 2005). The most heavily irrigated areas are in China and India, the world's most populated countries. Drip irrigation of closely spaced row-planted crops such as wheat and rice is not economic, therefore, the sprinkler or flood systems are common. Today, leisure industries and facilities such as football pitches, golf courses and tennis courts have adopted subsurface trickle irrigation systems to extend their availability, albeit at high costs.

"Fertigation" – "fertilization" plus "irrigation" – was applied to tomatoes grown on sand dunes in a field experiment performed in 1969 (Sagiv and Kafkafi., 1974), and Goldberg et al. (1971) reported the distribution of minerals and nutrients from a point source of irrigation to roots. Fertigation has now spread all over the world.

Benefits of drip irrigation and fertigation

Technological turning points in drip irrigation development in Israel

1960	Use of a perforated rubber tube for subsurface irrigation (Blass, 1964).
1965	First plastic linear-flow dripper produced by Netafim was used in the field in the southern Negev. Precipitated chemicals blocked the flow, which resulted in the development of the turbulent flow dripper (1970).
1976	Pressure-regulated dripper is developed, allowing constant flow in spite of pressure fluctuations of 3.5 atmospheres. It provides regulated flow and self cleaning.
1980	First use of drip irrigation in large areas of corn and cotton fields. Increases yields by ~25-35%.
1983	Enclosure of the dripper within a smooth tube is developed, to enable mechanical rolling and spreading (multi-season pressure regulation).
1990	Special stick-in drippers developed for greenhouse use.
2000	New family of integral drippers, especially suited for subsurface drip irrigation.

Expected benefits from fertigation

1. Improved nutrient availability.
2. Enhanced plant nutrient uptake.
3. Reduced fertilizer application rates and water requirements.
4. Minimized nutrients losses through leaching.

5. Prevents salt injuries to roots and foliage.
6. Reduced soil compaction, because of reduced surface traffic.
7. Decreased weed infestation.

Under-plastic-cover fertigation

1. Saves water by reducing direct evaporation from soil surface.
2. Prevents salinity buildup on soil surface.
3. Prevents weed infestation.
4. Reduces herbicide use.
5. Increases soil temperature if a clear plastic cover is used.
6. Reduces soil temperature if a reflecting cover is used.

Subsurface drip irrigation (SDI)

1. Increases water use efficiency by elimination of evaporative water losses.
2. Enables the use of recycled sewage water, by preventing plants exposure to pathogens.
3. Enables plants to escape morning frost damage.
4. Reduces fruit diseases by keeping the soil beneath the growing fruit dry.

Efficient use of water

The ultimate efficiency of water and fertilizer use can be achieved by matching the daily supplies of water and nutrients to demand, according to the plant development stage, with zero evaporation. André et al. (1978a, b) monitored daily demands for water and nutrients throughout the corn development cycle. When drip irrigation was applied in the field it was shown that plants took up all the daily supply and left nothing to neighboring plants (Abura and Kafkafi, 2002), which was evident from the sharp boundaries between treatments.

Fertigation, in any trickle irrigation technology, involves the injection of soluble fertilizer solutions into the irrigation systems via any dosing apparatus: dilution tanks, Venturi-type suction or by calibrated injection pumps. Commercial firms all over the world supply such equipment in all forms and sizes. The corrosive nature of fertilizers prevented the use of fertigation when aluminum or zinc-plated metal pipes were used for irrigation, but the introduction of plastics for containers, drip lines, pumps and connections enabled accurate fertilizer application through the irrigation lines. The fertilizer industry has adapted itself to field demands by introducing clean and soluble – albeit more expensive – fertilizers: soluble, acidic phosphate and potassium fertilizers with wide ranges of NPK ratios (IFA, 2005). The time pressure and the work load on the farmer arising from the need to prepare fertilizer solutions led to the development of services supplying liquid fertilizer blends according to specific recipes, as ordered by growers to meet specific plant demands, matched to particular growing stages and climatic conditions (Prenger et al., 2001). In the highly sophisticated industry of greenhouse cultivation, clean acid and bases are stored, and the instantaneous supply of nutrients to the irrigation line is controlled continuously, on site, by computer.

The conventional method of fertilizer application before planting becomes ineffective with drip irrigation systems. Growing tomatoes on sand dunes without a daily supply of P in the trickle line resulted in a complete exhaustion of P within a radius of 10 cm around the plants by the time it was needed for the developing fruits, but injection of a complete NPK fertilizer into the trickle line increased the yield by 30% (Ben Asher et al., 1974). An adequate supply of nutrients and water to satisfy plant demands from a limited soil root volume can be achieved only by matching the supplies of water and nutrients to plant needs during the various growth stages. Fertigation enables accurate supply of water and nutrients to the individual plant, whether it is a corn or a cotton plant in the field, or a single tree within an orchard. The daily application rate of fertigation changes during the growing season and is planned to follow plant daily demand according to its nutrients uptake strategy. Therefore, the units used in calibrating fertigation are milligrams of nutrient supplied per day per plant rather than kg/ha. Likewise, the unit for water supply is changing from the regular millimeters to liters per day per plant. Scaife and Bar-Yosef (1995) reported the daily consumption of water and nutrients by crops.

The fertigation technique has rapidly spread all over the world in the last 40 years, and irrigation controllers are available commercially that compensate for humidity, temperature and wind effects. In dealing with factors that modify temperature and humidity, a solar integrator can automatically increase the frequency of irrigations in sunny, hot dry weather and reduce it in dull, cool, damp weather. A rain override could also be used for outdoor crops: such a controller may initiate a single irrigation station as a trigger and then sequentially activate many other stations. All these instruments are based on physical measurements, but no easy-to-use, reliable, chemically activated automatic controllers are yet available for open-field crops or orchards. The quick development of trickle irrigation and fertigation systems in many parts of the world followed the demands to minimize water use in agriculture, which arose from the shortage of water caused by increasing urban demands. Development was also driven by increasing labor costs, demands to prevent pollution and to minimize soil erosion, increasing reliance on saline water sources, and unfavorable soil quality and wind conditions.

Fertigation reduces the amount of heavy work and minimizes the number of man hours involved in traditional methods of irrigation, such as furrow irrigation or flood irrigation. The ability to deliver an exact amount of nutrients and water to a specific plant in the field, at an exactly specified time under the remote control of a computer offers many advantages. It saves labor, avoids traffic movements on wet soils, thereby preventing compaction, saves water by avoiding delivery of water to unplanted areas such as traffic lanes and wide spaces between rows, minimizes evaporative water loss from bare soil by applying fertigation beneath plastic mulch. These advantages have made this system acceptable at all scales of agriculture production systems, from small-holdings to huge plantations. The ability to irrigate undulating soil surfaces enabled vineyards and tree plantations to be established in areas that were not accessible to agriculture before. However, the high costs of trickle systems have confined this irrigation method to locations where labor prices are high, water is scarce, and quality crops have a rich market that can cover the high investment costs.

The use of recycled sewage water

A particular development of surface and subsurface trickle irrigation is related to the increasing use of recycled sewage water for agriculture. Two main factors drive this development: 1) water shortage – sewage treatment systems and collecting dams for irrigation are already in use; and 2) because of environmental considerations, industrial effluents are reused and currently form about 70% of the water used in Israel's agriculture (Arlozoroff, 1996). Agricultural water use and comparisons with water resources worldwide were reported by the FAO (2005): the various regions differ markedly in their percentages of renewable water resources, in the decending order: Near East and North Africa – 51%, South Asia – 36%, East Asia – 8%, 90 developing countries – 8%, sub-Saharan Africa – 3%, and Latin America – 1%. Withdrawal of water for irrigation was estimated to account for only 8% per cent of the total renewable water resources of the 90 developing countries. However, there are wide variations between regions in the percentages of water used for irrigation: the Near East and North Africa use 53% of their water resources for irrigation, whereas Latin America uses barely 1%. The variations between individual countries are even wider: in 2000, ten countries used more than 40% of their water resources for irrigation, a situation which can be considered critical. An additional nine countries used more than 20% of their water resources for that purpose, a situation that may indicate that they are on the threshold of impending water scarcity. For several countries, relatively low national figures may give an overly optimistic impression of the level of water stress: China, for instance, is facing severe water shortage in the north, whereas the south still has abundant water resources. Already by 2000, two countries, Libya and Saudi Arabia, used volumes of water for irrigation which were several times larger than their annual water resources. Local groundwater mining also occurs in several other countries of the Near East, South and East Asia, Central America and the Caribbean, even if at the national level the water balance may still be positive.

Advantages of fertigation over fertilization

Fertigation has specific advantages over band placement or broadcast fertilization.

- Frequent supply of nutrients reduces fluctuations of nutrient concentration in the soil solution.
- Efficient and precise application of nutrients that matches changing plant physiological demands.
- Fertilizers are supplied only to the irrigated soil volume.
- Nutrients can be applied to the soil to compensate for nitrogen (N) leaching caused by excessive rains, when soil or crop conditions would prohibit entry into the field with conventional equipment.

Drip fertigation has further advantages (Haynes, 1985) over other methods of fertigation such as sprinkle irrigation.

- Increased fertilizer use efficiency, because nutrients are applied only to the active root zone, which reduces losses of nutrients through leaching or soil fixation.
- The crop foliage remains dry, thus reducing incidence of pests or diseases, and avoiding foliage burn.
- Fertigation can be applied under all weather conditions; it is unaffected by wind, and is free of the runoff associated with sprinkler irrigation.
- It is the most suitable method for protected and plastic-covered crops.

Drip fertigation systems

Each drip fertigation systems is designed for a specific combination of crop, climate and soil, and comprises the following components in conjunction with a drip irrigation system.

Fertilizer delivery

There are two main methods. 1 – Fertilizer dilution tanks, which are usually used in small plots, are connected to the head of the irrigation line, and deliver predetermined quantities of fertilizer during the irrigation cycle. 2 – External pumps, which are used to cover large areas, inject the fertilizer solution under positive pressure (usually that of the water supply) directly into the irrigation line. The latter method is supposed to deliver a constant concentration of fertilizer during the irrigation cycle.

Filtration

Filtration is a prerequisite in drip irrigation, to avoid clogging of drip lines and emitters, and to maintain the uniformity of water and fertilizer application. The type of filtration system depends on the quality and source of the water supply, and the water quality and composition must be taken into consideration at the planning stage of the fertigation systems, especially when a subsurface installation is considered. In the case of deep well water sources the system should remove gravel, sand or suspended materials. Open surface waters (ponds, rivers or lakes) may contain organic matter and algae that must be removed before entry to the lines. In fertigation systems a second filtration step after the fertilizer container is necessary, to remove any particulate matter or precipitates from the fertilizer mixtures. Deep well water sources may contain soluble divalent iron, which, on contact with phosphate, may produce a gel-like precipitate that can block the tricklers and filters.

Distribution of water and nutrients in soil

Water flow

Two main forces – gravity and capillarity – govern the movement of water in the soil.

In drip irrigation, water spreads from a dripper in three dimensions and creates a wetted front of various shapes (Bressler, 1977), depending on the soil type and the water discharge rate. When the trickle discharge rate is higher than the soil infiltration rate, lateral water movement dominates and shallower penetration is to be expected albeit with larger wetted soil surface area with a given amount of water.

Nutrient movement

Strongly sorbed ions, such as phosphate, are less mobile in soils than non-sorbed ions, such as nitrate or chloride (Kafkafi and Bar Yosef, 1980). During repeated fertigation cycles there is a balance between the lateral spread of water and evaporation, as a result of which soluble salts might accumulate at the border between the dry and the wet zones, especially in hot dry areas with no dry-season rainfall (Kafkafi and Bar Yosef, 1980). The salt accumulated at the wet zone periphery can reach very high levels and, a single flush of rain could wash this salt into the root zone and cause considerable damage.

Plastic covers

To avoid soluble salt accumulation on the soil surface because of evaporation, irrigation under a plastic cover is used, especially when saline water is the only source for irrigation. In an arid climate zone, where the evaporation rate is high, mobile nutrient anions (NO_3^-, Cl^-,), together with the cations Na^+ and Ca^{2+} may accumulate around the wet zone periphery on the soil surface. This zone of highly concentrated soluble salts is detrimental to young seedlings, because their restricted root system might be exposed to high salt concentrations, even with good-quality water.

Selection of fertilizers

Most water-soluble and liquid fertilizers are suitable for fertigation. In selecting a fertilizer four main factors should be taken into consideration.

1. Plant type and stage of growth.
2. Soil conditions.
3. Water quality.
4. Fertilizer composition and price.

Type of plant

Plant sensitivity to the form of N increases during the fruiting stages (Xu et al., 2001). Some plants, such as tomato, are very sensitive to high ammonium concentration near the roots, therefore, nitrate-rich nutrient solutions should be selected (Kafkafi et al., 1971).

Soil and water conditions

At elevated root-zone temperatures ammonium might damage the roots by competing with the sugar needed to root respiration. Local high ammonium concentration can result in ammonia toxicity to root cells. In cold root zones ammonium is a safe N source, since less sugar is consumed for respiration by root cells (Ganmore-Newmann and Kafkafi, 1983).

On heavy clay soils, a zone of water ponding might develop under the trickler outlets. In this wet soil volume, at high soil temperatures, local anaerobic conditions might cause severe nitrate-N losses to the atmosphere, as N_2 or N_2O. Under such conditions the plants might suffer from N deficiency in spite of receiving a nitrate supply through the irrigation line. In such cases, low concentrations of N in the form of urea or ammonium sources in the irrigation solution might prevent the N losses and deficiency caused by denitrification. In heavy clay soils, the ammonium concentration in the soil solution will always be below the root-damaging level, because of preferential sorption to soil surfaces. It may be necessary to lower the pH of the irrigation water to about 5.5, in order to keep the phosphorus (P) in the solution during the fertilizer injection, and to prevent blockage of the tricklers. Phosphorus application as phosphoric acid is preferable during cold seasons; it serves to remove precipitates and to supply P to the slow-growing roots. If micro-nutrients are needed, their soluble chelated forms are less subject to precipitation in the irrigation lines, and they move in the soil with the water towards the roots.

Fertilizer characteristics

Solid fertilizers vary in their dissolution rates and in the amount that can be dissolved in a given volume of water at a specific temperature. The solubility generally decreases when two or more fertilizers are mixed together. This characteristic is crucial to the fertilizer choice. Solubility generally increases with temperature, but because of their endothermic reaction, nitrate salts lower the solution temperature. When the fertilizer tank is placed in an open field low ambient temperatures could cause solid precipitation in the tank and could block the drippers. The diverse solubility characteristics of the various fertilizers, and the problems they cause in field operations stimulated the establishment of "fertilizer dilution services", which provide a nutrient cocktail according to the farmer’s order, to meet the specific crop needs at the appropriate times throughout the growing season.

Another approach to solving the solubility problem was adopted in the advanced greenhouse industry, where separate tanks of nutrient sources, acids and bases are used. With the help of a computer it is possible to calibrate the appropriate dose of each nutrient element to be pumped into the irrigation line, so that the concentration of the mixture remains low and precipitation is prevented. This technology is too expensive to operate in large open fields and plantations, where Venturi-type or proportional pumps are used to inject the dose of fertilizer solution from a storage tank into the irrigation line.

Urea, ammonium nitrate, calcium nitrate, potassium nitrate and ammonium phosphate, are soluble in water and are used extensively to prepare single- or multi-nutrient fertilizer solutions. Mono-ammonium phosphate, phosphoric acid and urea phosphate are also water soluble, but they may precipitate when injected at high rates into “hard” water, i.e., containing high concentrations of calcium and magnesium carbonates. All potassium fertilizers are water-soluble but vary in their rates of dissolution and their sensitivity to temperature; KCl is the most widely used potassium fertilizer for field crops.

Compatibility of fertilizers

Mixing two fertilizers can sometimes result in precipitation. For example, injection of a calcium salt with phosphate or sulfate may increase the likelihood of calcium phosphate or calcium sulfate precipitation, even at low pH. The pH of the irrigation solution should be within the range 5.5 to7.0. Too high a pH will reduce the availability of P, Zn and Fe, and may result in precipitation of Ca and Mg phosphates or carbonates in the irrigation lines. Too low a pH is detrimental to roots and may increase Al and Mn concentrations in the soil solution. Nitric (HNO_3) or phosphoric (H_3PO_4) acids are used to lower the pH level in fertigation. Their advantage, besides dissolution of basic precipitates in the line, is that they also supply the plants with the essential nutrients, and thereby replace N and P fertilizers. In saline waters and calcareous clay soils nitric acid increases Ca dissolution and thereby minimizes salinity injury, because of Ca/Na competition, and reduces the chloride salinity in the root zone, because the nitrate counterbalances excess chloride (Xu et al., 2000).

Precipitation in the irrigation lines

Precipitation of insoluble di-calcium phosphate, di-magnesium phosphate and calcium carbonate, could develop when high-pH water is used. Iron phosphate, originating from wells containing divalent iron, might precipitate in drip lines even at low pH water. Water containing high concentrations of Mg ions might cause ammonium magnesium phosphate precipitation in the fertilizer tank. Avoiding the use of ammonium fertilizer in such conditions can avoid the risk of blocking the emitters. Using K_2SO_4 or $(NH_4)_2SO_4$ with water containing high concentrations of calcium might result in $CaSO_4$ (gypsum) precipitates that could clog the drip lines.

Scheduling fertigation

Nutrient elements are taken up according to plant demands at a specific development stages (André et al., 1978 a, b). Fertigation, i.e., injecting fertilizer into a drip irrigation system, offers the benefits of supplying the correct amounts of nutrients to the crop at the times when they are most needed by the plants, directly into the root zone. Fertigation scheduling depends upon climatic factors, soil type and the fertilizer requirements of the growing plants. The uptake rates of nutrients (N, P and K) during growth of field and vegetable crops were summarized by Bar Yosef (1999). Climatic conditions, soil type, system design, and length of the growing season and other plant characteristics determine the frequency of fertilizer application. In plants grown on sand dunes, several irrigations per week might be needed, whereas on clay soils one or two irrigations per week might be sufficient. The smaller the root volume, the higher the necessary frequency of fertigation.

Nutrients behavior in soil

Soil chemical properties are an important factor in planning fertigation. The pH strongly influences the availability of residual nutrients in the soil and also of those added via fertigation. The balance between the uptake of cations and of anions by the plant affects the pH in the rhizosphere (Marschner, 1995). Nitrate and ammonium are the main forms of N available for plant uptake. When a plant takes up more nutrient cations than anions, as occurs when NH_4^+ is the main N source, protons are exuded by the roots and acidify the rhizosphere. If the anion uptake is predominant, as when NO_3^- is the main source of N, the roots exude OH^- or HCO_3^-, which results in a pH rise in the rhizosphere. The rhizosphere pH varies with the form and concentration of the N fertilizer, but the extent of the pH change in the zone around the root depends on the buffer capacity of the soil.

The cation exchange capacity of the soil is an important consideration in determining the amount of cations to be added during fertigation, and the frequency of addition. In most agricultural soils and irrigation waters, calcium and magnesium are present in larger quantities than needed by any crop, and their supply to the plants is usually satisfied by water mass flow (Barber, 1962). Potassium is the main cation that must be supplied with the irrigation water, and in order to ensure the maintenance of an acceptable concentration of potassium in the soil solution, a soil with a low cation exchange capacity (CEC) must receive fresh supply of potassium more frequently than one with a high CEC, that can hold higher quantities of potassium. Fertigation is most practicable in sandy soils and those in dry and arid regions that have low CEC, since these soils need frequent irrigation and quick replenishment of nutrients. Old farming practices regarded sand dunes as non-agricultural soils, but the introduction of fertigation turned desert sand dunes into productive agricultural soils (Kafkafi, 1994). The most important aspect of fertigation, globally, is that it offers the possibility to expand human activities into areas never before used for irrigation. The need to saving water in the traditional areas of irrigation, and the loss of existing productive fields in the face of urban growth could provide the stimulus to move water and agricultural production to desert areas.

Nitrate (NO_3^--N) is highly mobile and is more likely to be lost through surface runoff, denitrification during flood irrigation, and leaching. In trickle irrigation, ponding under the tricklers, especially in clay soils, creates an oxygen-deprived space in which denitrification is observed during the irrigation cycle (Bar Yosef, 1999). The rate of water discharge from a dripper should not exceed the rate of water entry into the soil from a point source. Hydrolysis of applied urea can result in ammonia toxicity and losses in the form of gaseous NH_3, but acidification of the irrigation water prevents such direct losses of ammonia from urea fertilizers.

Added phosphate is adsorbed or precipitated in the soil, leading to a rapid decline in the water-soluble phosphate concentration in the soil solution. Movement of phosphate is impeded because of retention by soil oxides, carbonates and clay minerals. Application of P via drip irrigation is more efficient than via sprinkler irrigation or broadcasting, because fertigation supplies P directly into the active roots zone, which enables its immediate uptake, before it undergoes drying and irreversible fixation in the soil.

Root growth

To achieve optimum plant growth, the root zone must be well supplied with water, nutrients and oxygen, and must suffer minimal soil compaction. Maintenance of the water potential by frequent irrigation at continuous low water tension, especially in clay soils, might lead to a sub-optimal supply of oxygen in the root zone (Silberbush et al., 1979). Roots respond within minutes to a reduction in oxygen supply by cessation of root extension, and the elongation zone of a cotton root, for example, dies after only 30 min without oxygen (Klepper, 1981). Under drip irrigation, oxygen might be excluded from the saturation zone when there is a continuous supply of water at high rates, but a slow flow rate may maintain optimal moisture and oxygen regimes in the wet soil volume.

The nitrate-to-ammonium ratio affects the development of the root system: high concentrations of ammonium are deleterious to root growth, especially when soil temperatures are high, i.e., under plastic or in growth containers. At high root temperature sugar in the root cells is required for respiration and for ammonium metabolism. If the supply of sugar from the leaves, lags behind it's consumption in root cells, the resulting temporary excess of free ammonia kills the root cell (Ganmore-Newmann and Kafkafi, 1983). At high temperatures around the roots, especially under soilless cultivation conditions, nitrate-N is a safer N form during fertigation. At low root temperature NO_3^- accumulates in the roots, resulting in N deficiency (Ali et al., 1994). Thus, the concentration and form of N applied in fertigation should be adapted to the differing conditions of the winter and summer seasons, and according to specific crops demand and sensitivity. In general, monocotyledon roots are less sensitive to ammonium in solution than dicotyledon ones (Moritsugo et al., 1983).

Subsurface drip irrigation and fertigation (SDI)

Seasonal installation and removal of drip lines increase production costs in wide-row field crops. Subsurface drip irrigation became a common practice in the USA following its introduction about 1960, but interest in the technology has greatly expanded since the early 1980s. Yield responses for over 30 crops indicated that crop yield for subsurface drip was greater than or equal to that obtained with other irrigation methods, including surface drip, and required less water in most cases. Laterals are installed at depths ranging from 0.02 to 0.70 m, and lateral spacings range from 0.25 to 5.0 m. Injection of nutrients, pesticides, and other chemicals to modify water and soil conditions is an important aspect of subsurface drip irrigation. Irrigation water use for corn can be reduced by 35-55% by using SDI, compared with traditional forms of irrigation (Camp, 1998). The deep position of the tricklers significantly increased the P and K contents at the center of the root zone. The enhanced concentration apparently stimulated plant rooting which, together with the higher nutrient activity in the soil solution, increased P and K uptake rates, which, in turn, facilitated greater dry matter production and commercial yield than were obtained with surface trickler placement (Hernandez et al., 1991). Slow-release chemicals embedded in filters prevent root entry and clogging of the drippers. In addition to cost effectiveness and energy saving, subsurface drip fertigation has added agronomic advantages over surface drip fertigation: 1) placement of nutrients in the region where root activity is maximal and the daily and seasonal temperature fluctuations are low; and 2) the top 4-5 cm soil layer remains dry, thereby reducing the evaporation losses and inhibiting weed germination.

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Ecological Intensification of Agriculture and Implications for Improved Water and Nutrient Management

Kenneth G. Cassman

Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE 68583-0724, USA. E-mail: kcassman1@unl.edu.

Abstract

Econometric models predict that global cereal demand will increase by 1.3% annually through 2025; cereal yields must increase by 1% annually to meet this demand. This scenario assumes a 50-Mha increase in cereal production area. However, recent trends suggest that the cereal production area will stay constant, at best, or may decrease slightly because of land conversion for other uses. Likewise, rising costs of fossil fuels are driving the diversion of grain for production of biofuels and bio-based industrial feedstocks. It is, therefore, plausible that current econometric models underestimate cereal demand and the rate of yield increase that will be needed to meet it. The rate of increase in cereal yields is decidedly linear; it is falling below the rate of increase in demand, and would do so more rapidly under a scenario in which cereal demand is greater and the cereal production area smaller than forecast by current econometric projections. There is a need for accelerated yield gain – combined with protection of natural resources and environmental quality for future generations. Ecological intensification of cereal production systems provides the framework for achieving these dual goals. It involves concomitant improvements in nutrient use efficiency, especially of nitrogen (N), water use efficiency, and energy efficiency. Fertigation holds tremendous promise for contributing to ecological intensification in irrigated systems, because it facilitates improved congruence, in time and space, between crop nutrient demand and the available nutrient supply. With advanced irrigation technology, such as low-pressure sprinkler systems or drip irrigation, fertigation can help sustain the required rate of yield gain while also achieving a substantial decrease in nutrient and water requirements per unit of grain production.

Keywords: food security, crop yield potential, nutrient use efficiency, environmental quality, irrigated agriculture.

Introduction

The rapid economic development that has occurred in Asia during the past 30 years was supported by low commodity prices for the major food crops. Reasonable food prices were especially important for the development turnaround since 1990 in countries like China, India, Thailand, and Vietnam. Indeed, reasonable food prices will be required to sustain rapid economic development in these countries and worldwide.

Economic development is accompanied by increased demand for land and water for: expansion of industry, improvement of living conditions, expansion of the range of recreational activities, and the conservation of natural resources. Thus, the per capita consumption of land and water increases with economic development, which results in intensified competition between agriculture and other economic sectors, for land and water resources. At issue is whether there is enough good arable land to sustain the increases in crop production that are required to meet the demands of a much larger and wealthier human population without causing shortages that would drive up food prices substantially, and without causing environmental degradation.

To examine this issue requires accurate prediction of future trends in crop production, and of the land area and water available for crop production. Because much of the negative impact of agriculture on environmental quality results from nutrient losses associated with intensive cropping systems, the trends in nutrient use efficiency and the technologies to increase it must also be considered. This paper will, therefore, investigate production trends of the major cereal crops – maize, rice, and wheat – to gauge whether current trajectories are sufficient to meet human food needs in the coming decades. Underpinning issues are the rate of gain in yield, the land area available for crop production – especially the trends in irrigated area, the technologies needed to improve nutrient use efficiency, and the role of fertigation. Emphasis is placed on the three major cereals because they contribute more than 50% of all human energy intake, eaten either directly or indirectly as livestock products, and because they receive about 57% of all commercial fertilizer used in agricultural production (Cassman et al., 2003).

Projected Food Demand and Supply

Future global food demand can be estimated from the rates of population growth and of economic development, summed globally on a country by country basis. The economic development rate is an important parameter because human diets include a greater diversity of food sources and increased consumption of meat and livestock products as income levels rise. These trends follow the same general pattern, regardless of culture, religion, or geographical location (Delgado et al., 2002). Because 2-4 kg of grain are required to produce 1 kg of meat or fish, grain demand will rise faster than the rate of population increase.

Food supply can be predicted from trends in crop yields and in the arable land area available for crop production, and econometric models have been developed to predict global food demand and supply. One of the most influential and comprehensive food supply-demand models is the IMPACT model developed by Mark Rosegrant et al. (2002) at the International Food Policy Research Institute in Washington, DC. According to the IMPACT model, demand for the three major cereals is projected to increase at a compound annual rate of 1.29% from 1995 to 2025 (Table 1). This increase is predicted to come from increases in cereal yields (0.98%/yr) and an expansion of the crop growing area by 50 Mha.

Table 1. Prediction of global aggregate demand, supply, and yield of the three major cereals (maize, rice, and wheat) from 1995 to 2025, by the IFPRI-IMPACT model‡, and a modified prediction based on updated trends in land use.

	1995	2025	Annual rate of change	Modified 2025 prediction	Modified annual rate change
			%		%
Population (10^9)	5.66	7.90	1.12	Same	1.12
Demand (million mt)	1,657	2,436	1.29	2,558	1.46
Production area (million ha)	506	556	0.31	491	-0.10
Mean grain yield† (kg/ha)	3.27	4.38	0.98	5.21	1.56

‡ Rosegrant et al., 2002, International Food Policy Research Institute.
While the IFPRI-IMPACT prediction accounts for grain demand for human food and livestock feed, it does not consider grain used for biofuel or bio-based industrial feedstock production; the modified prediction assumes that 5% of global grain supply in 2025 is used for production of biofuel and bio-based industrial feedstocks.
†Weighted average for the three major cereals.

However, small changes in the assumptions that go into such econometric models can have large impacts on the resulting prognosis for meeting future food demand. In contrast to the IMPACT model's projection of increased land area for cereal crop production, actual land-use trends indicate that there has been no increase in area devoted to the three major cereal crops since 1980, while the area devoted to all cereal crops (including maize, rice, wheat, sorghum, millet, oats, and other minor grain crops) has been decreasing by 2.1 Mha per year since 1981 (Fig. 1). Given the rapid increase in economic development, it is plausible that the land area available for the major cereals will decline somewhat in the coming decades, in response to demands for better housing, roads, recreation, and expansion of industrial facilities.

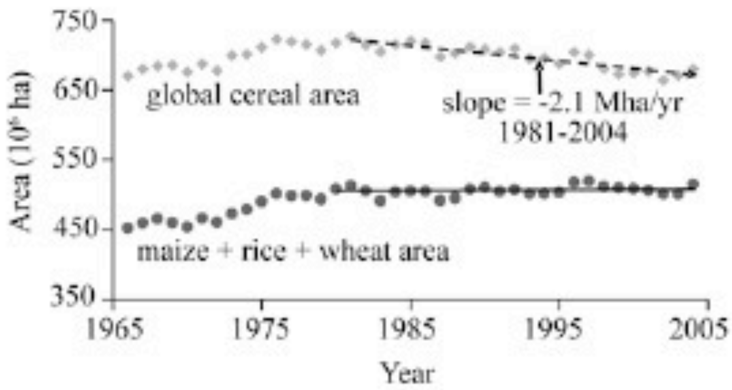

Fig. 1. Global trends in production area of all cereal crops (data at top) and to the three major cereal crops maize, rice, and wheat (data at bottom).
Source: http://faostat.fao.org.

Most of this development will occur in the peri-urban areas surrounding cities – areas that are typically located in regions with highly productive agricultural soils. In contrast, there are few remaining uncultivated areas with good-quality soils, so that replacement of cereal-growing areas lost to development will be with land characterized by ever more marginal soils, in harsher climates not suited to intensive cropping systems.

In addition, the IMPACT model primarily considers grain use for human food and livestock feed, and does not take into account the increasing use of grain as an industrial raw material for biofuels such as ethanol, or as a source of industrial feedstocks such as starches or plastic precursors. In the USA, in 2004, about 11% of the maize crop was used for ethanol production, and this will double over the next 7 years, under the new Energy Bill recently passed by the US Congress. Concern about high energy prices has motivated a number of other countries to increase production of ethanol and industrial feedstocks from grain. Therefore, it is likely that at least 5% of global grain production could be used for biofuel and bio-based industrial feedstock production by 2025.

If we take into account the increased use of grain for biofuels and bio-based products, and a small annual decrease of 0.1% in the area dedicated to growing the major cereals, we obtain a very different scenario for the food demand-supply balance. Under this scenario, global demand for maize, rice, and wheat will increase by 1.46% annually, compared with the required rate of yield increase of 1.56% per annum (Table 1).

Yield trends

Yields of the major cereals have been increasing steadily, but unlike the projected demand, which is predicted to increase at an exponential rate of increase of 1.29% annually, according to the baseline scenario of the IMPACT model (Table 1), the rates of increase in yields are decidedly linear (Fig. 2). Thus, the rate of yield increase is declining relative to the average yields. For example, the relative rates of increase of the average maize, rice, and wheat yields ranged from 2.62-2.93% in 1966, and had fallen to 1.24-1.42% of the average yields in 2004 (Table 2). Moreover, the proportional rate of gain will continue to decline as long as average grain yields maintain their linear rates of increase. In fact, the relative rate of gain in cereal yields will fall below the baseline IMPACT scenario rate of increase in cereal demand within the decade.

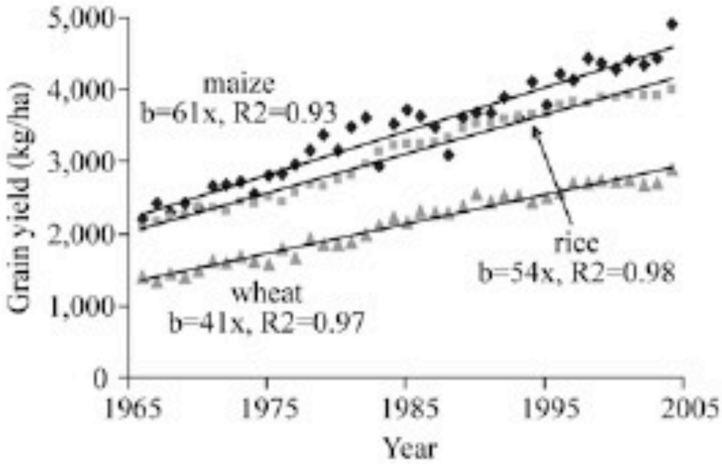

Fig. 2. Global trends in yield of maize, rice, and wheat from 1966-2004. Linear regression slopes (b) represent the annual rate of yield gain in kg/ha/yr. Source: http://faostat.fao.org.

In light of the more realistic scenario of declining land area devoted to cereal crop production and increasing global use of grain as a raw material for biofuel

and industrial feedstocks (Table 1), the linear trends in grain yield are currently well below the rates of increase in demand for the major cereals. Unless the improvements in cereal yields accelerate, this scenario presents a prospect of rapidly increasing grain prices and even the specter of grain shortages.

Table 2. Global rate of increase in yield of maize, rice, and wheat, 1966-2004.

Crop	Mean yield		Rate of gain	Proportional rate of gain	
	1966	2004		1966	2004
	-------- kg/ha --------		kg/ha/yr	----------- % -----------	
Maize	2,210	4,907	61.0	2.76	1.24
Rice	2,076	4,004	54.5	2.62	1.36
Wheat	1,408	2,907	41.2	2.93	1.42

The need for ecological intensification

While it could be argued that increased grain prices would stimulate the expansion of cropped areas, there are two factors that make this option unlikely, or at least undesirable. First, as mentioned earlier, there is little remaining uncultivated land with adequate soil quality in regions with climates that are favorable to intensive cereal crop production. In fact, most of the remaining land is of poorer quality than the existing cereal land that is being diverted to other uses. Second, a large proportion of the uncultivated land that is capable of supporting crop production supports natural ecosystems, such as rainforests, grassland savannah, and wetlands, all of which provide critical habitats for conservation of plant and animal species. Expanding cultivated systems at the expense of these natural ecosystems would threaten the biodiversity they contain and the ecosystem services they provide.

A more desirable outcome would involve the ecological intensification of major cropping systems – especially those that produce the major cereal crops (Cassman, 1999). Ecological intensification implies the achievement of substantially higher yields relative to both land area and time, by means of crop and soil management practices that protect soil and water quality. Such ecologically intensified systems would be a departure from the intensification associated with the initial phases of the green revolution, which led to considerable negative impacts on ecosystems, because of the effects of inefficient and sometimes ineffective use of pesticides and fertilizers (Matson et al., 1997; Tilman et al., 2002). Since then, the use of integrated pest management and improved fertilizer management has demonstrated the potential for a more ecological intensive agriculture.

Growing importance of irrigated agriculture

Irrigated agriculture has expanded rapidly during the past 40 years, from 153 Mha in 1966 to 277 Mha in 2002 (Fig. 3). Moreover, global food security is more dependent on irrigated agriculture today than in the past, because the irrigated area now forms 18% of all cultivated land, compared with 11% in 1966, and it currently accounts for about 40% of our global food supply.

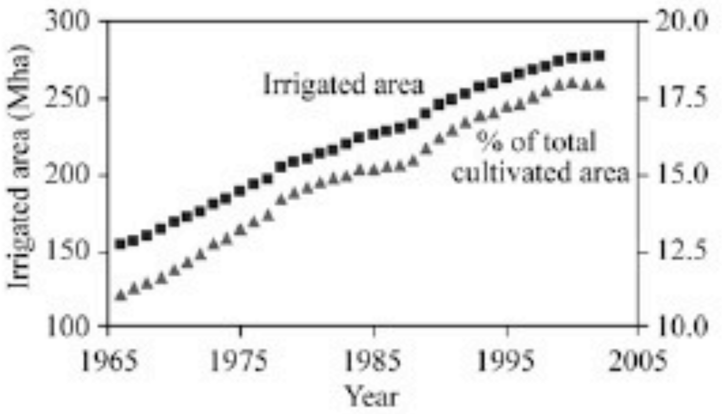

Fig. 3. Trends in total global irrigated crop area and % total cultivated area. Source: http://faostat.fao.org.

Irrigated agriculture currently uses about 70% of the fresh water estimated to be available globally for use each year (Postel, 1998). However, increasing competition for water between agriculture and other users will require producers of irrigated crops to be increasingly more efficient, so that the yield per unit of applied water must increase substantially. At the same time, because of the importance of irrigated agriculture to the global food supply, the farmers who use irrigation must sustain or even accelerate the rates of increase of crop yields. Fortunately there are a number of existing technologies that can greatly improve water use efficiency, compared with the traditional flood or furrow irrigation. Low-pressure pivot irrigation and sub-surface drip irrigation systems are good examples of such technologies, although such systems require substantial capital investment. However, when these systems are coupled with improved methods for scheduling irrigation and controlling the amount applied, it is possible to achieve significant increases in both crop yields and water use efficiency (WUE).

Environmentally sound nutrient management in high-yield systems

Higher grain yields require greater uptake of crop nutrients, because the relationship between crop biomass yield and nutrient uptake is tightly conserved. This tight conservation is especially true for N (Greenwood et al., 1990), which is the plant nutrient of greatest concern because of the negative impacts of N losses on water quality and greenhouse gas emissions (Galloway and Cowling, 2002; Matson et al., 2002). Losses of phosphorus, and the associated effects on water quality, are also a matter for concern in heavily manured cropping systems.

The challenge, similarly to that with water, is to produce higher grain yields while at the same time achieving greater N fertilizer efficiency. The focus here is on commercial N fertilizers. Although organic N sources are an important source of the nutrients used in crop production, their relative contribution continues to decline because there is simply not enough manure to meet crop N requirements, worldwide (Sheldrick et al., 2003). The same is true for the other macro-nutrients.

However, achieving higher N-fertilizer use efficiency (NUE) in high-yield crop production systems is difficult, because the response to N follows a diminishing-return function (Cassman et al., 2002, 2003). Hence, the marginal responses to increased N applications decrease for all components of N efficiency as yields approach the potential ceiling (Fig. 4). In fact, the average NUE achieved by farmers is quite low in high-yield cereal production systems: 31% for irrigated rice in Asia, 18-49% for irrigated wheat in rice-wheat systems of India, and 37% for rainfed maize in the USA Corn Belt (Cassman et al., 2002).

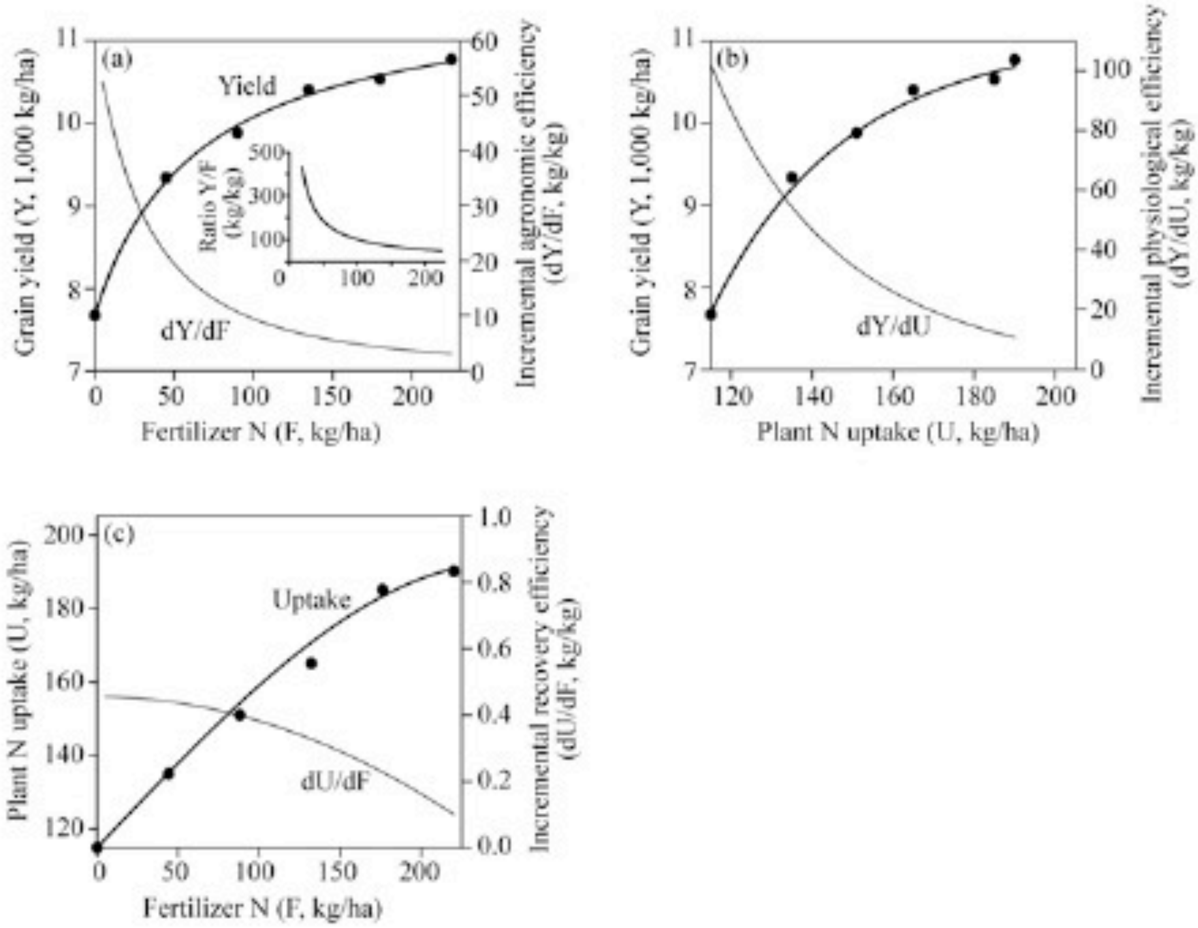

Fig. 4. Relationships among grain yield, plant N accumulation, and the amount of N applied to irrigated maize, and their effects on different components of N-use efficiency. Measured values (symbols) and fitted curves are based on a field experiment conducted in eastern Nebraska. The experiment represents a favorable environment, with fertile soils, use of a well adapted hybrid, and good pest control. (Cassman et al., 2003).

Greater NUE can be achieved, however, by improving the congruence between the immediate N demand of the crop and the N supply from both indigenous soil N resources and applied N fertilizer (Cassman et al., 2002; Dobermann and Cassman, 2002). Such tactics reduce N losses by decreasing the amount of inorganic N in the soil system that is in excess of the short-term crop demand, and which can be lost through leaching, denitrification, volatilization, or runoff. Both yield and NUE under on-farm conditions can be greatly improved by means of technologies such as: multiple split applications; real-time sensing of plant N status with a chlorophyll meter, to guide N application timing; and site-specific or field-specific N management, in large or small fields, respectively (Olk et al., 1996; Peng et al., 1996; Dobermann and Cassman, 2001; Dobermann et al., 2002; Wuest and Cassman, 1992). Controlled-release fertilizers also show promise for improving NUE, by increasing the congruence between N supply and crop N demand (Shoji and Kanno, 1994).

Fertigation and ecological intensification

Fertigation enables the application of N and other nutrients in multiple small doses that can be timed to achieve congruence with crop demand. Like other methods of N application, however, fertigation requires the real-time estimation of the crop N status and N demand, to ensure that N is applied at the proper times and in the correct amounts. When coupled with an efficient irrigation system, such as a low-pressure pivot or lateral-moving sprinkler systems, or drip irrigation, it is possible to achieve very high levels of both NUE and WUE. Fertigation is particularly useful on crops that have a large N requirement, because it is relatively easy to apply a large number of N doses, in order to avoid excess N supply, which would increase the risk of N losses and luxuriant vegetative growth. In contrast, fertigation may not improve NUE when used with a furrow irrigation system, unless the irrigation can be applied in uniform amounts across the field (Vories et al., 1991; Alva and Paramasivam, 1998). In the case of small flood-irrigated rice fields in China, however, irrigation uniformity is not a problem, and there appears to be a significant increase in NUE as a result of using fertigation (Chen et al., 1989).

Fertigation via drip irrigation can help to improve the use efficiencies of P and K, also, especially in soils that contain minerals that fix these nutrients in unavailable forms. Examples are highly weathered P-fixing tropical soils and K-fixing vermiculitic soils. Under these conditions, fertigation with a drip system allows fertilization to be applied to a smaller soil volume, which in turn ensures greater nutrient availability in the fertilized zone than would be obtained with a broadcast-incorporated application. The result can be greater nutrient uptake from the applied fertilizer (Barber, 1984; Ouyang et al., 1999).

In conclusion, the ultimate challenge is to sustain increases in crop yields that are sufficient to meet a substantial increase in food demand, while protecting water resources from nutrient contamination and reducing the release of greenhouse gases, especially nitrous oxide. An added challenge is to achieve this increase in food production while using less irrigation water, because of the increasing diversion of water supplies to uses other than crop production. Fertigation holds tremendous promise to assist in the ecological intensification of major food crop systems, because it facilitates the optimization of both nutrient- and water-use efficiency.

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Role of Mineral Nutrients in Tolerance of Crop Plants to Environmental Stress Factors

Ismail Cakmak

Sabanci University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey. E-mail: cakmak@sabanciuniv.edu.

Abstract

Around 60% of cultivated soils worldwide have plant-growth-limiting problems caused by mineral nutrient deficiencies and toxicities. Therefore, improving the mineral nutritional status of plants under marginal environmental conditions is of great importance for maintenance of crop productivity. In most cases plants growing under marginal environmental conditions (e.g. salinity, low and high temperatures, and drought) receive much more sunlight than they can utilize in photosynthetic electron transport and CO_2 fixation. This causes excessive accumulation of absorbed light energy and of photoreductants in the chloroplasts, which leads to activation of molecular O_2 to reactive oxygen species (ROS). When ROS are not adequately scavenged, photooxidative damage occurs in the chloroplasts, and leads to chlorophyll damage, lipid peroxidation and, consequently, cell death. By limiting the utilization of absorbed light energy in photosynthesis, environmental stress factors increase the potential for photooxidative damage in chloroplasts. Because an adequate supply of mineral nutrients is indispensable for maintenance of photosynthetic electron transport and carbon metabolism, impairment of the mineral nutritional status of plants under marginal environmental conditions can exacerbate photooxidative damage and limit plant performance. In the present study, several examples are given, which show that plants exposed to environmental stresses require additional supplies of mineral nutrients, particularly nitrogen (N), potassium (K), magnesium (Mg), calcium (Ca) and zinc (Zn) to minimize the adverse affects of stresses. Enhanced production of ROS in plants under marginal conditions is not caused only by impairment of photosynthetic electron transport. It appears likely that an NADPH-dependent oxidase is another important source of ROS, which is stimulated by drought, chilling, and/or salinity. Of the mineral nutrients, K and Zn seem to interfere with the NADPH-oxidizing enzyme and thus to provide additional protection against damaging attack of ROS under salinity, drought and chilling stress. It is concluded that improving the mineral nutritional status of crop plants is of great importance for

minimizing detrimental effects of environmental stress factors on their growth and yield.

Keywords: Co_2 fixation, carbon metabolism, reactive oxygen species, photooxiddative damage.

Introduction

Crop plants are often exposed to various environmental stress factors, such as drought, soil acidity, salinity and extreme temperatures, which severely affect soil productivity and crop production, worldwide. Bray et al. (2000) estimated that the contribution of environmental stress factors to global losses in crop production is becoming increasingly important. Fig. 1 shows that the relative decreases from the record yield capacity (maximum yield under ideal growth conditions) caused by abiotic stress factors vary between 60 and 82% for corn, wheat and soybean. In the case of wheat and soybean, record yields are 14.5 and 7.4 mt/ha, respectively, but the current worldwide average yields are 1.9 and 1.6 mt/ha, respectively (Fig. 1).

In comparison with the yield capacity losses of wheat and soybean caused by biotic stress factors, those caused by abiotic stress factors are much greater. Most of the yield losses caused by abiotic stresses are attributed to drought, salinity, extreme temperatures, acidity, and impairments of the mineral nutritional status of plants, i.e., deficiencies and toxicities. Recently, Cakmak (2002) reported that at least 60% of cultivated soils worldwide have growth-limiting problems arising from mineral nutrient deficiencies and toxicities. Combinations of such soil nutritional problems with other environmental stress factors such as drought, salinity, chilling, etc. are responsible for severe losses in crop production worldwide.

Survival and productivity of crop plants exposed to environmental stresses are dependent on their ability to develop adaptive mechanisms to avoid or tolerate stress. Accumulating evidence suggests that the mineral nutritional status of plants greatly affects their ability to adapt to adverse environmental conditions. In the present paper the role of the mineral nutritional status of plants in their adaptation to environmental stress conditions will be discussed, with emphasis on abiotic stress factors. Of the mineral nutrients affecting plant adaptation to stress conditions, nitrogen (N), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn) and boron (B) are the most extensively studied, therefore, special attention will be paid to them.

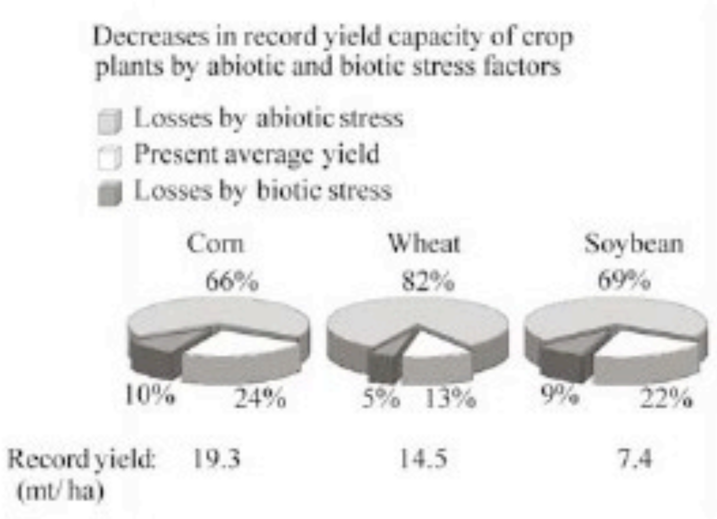

Fig. 1. Record yields (yields under ideal conditions) and decreases from the record yield capacities of corn, wheat and soybean plants, caused by abiotic and biotic stress factors (Bray et al., 2000).

High-light stress and photooxidation

Photooxidative damage, i.e., light-dependent generation of reactive oxygen species (ROS) in chloroplasts, is the key process involved in cell damage and cell death in plants exposed to environmental stress factors (Foyer et al., 1997; Asada, 2000; Foyer and Noctor, 2005). As shown in Fig. 2, chloroplasts are the main sites of ROS formation, and photosynthesis electron transport provides the main means of formation of ROS such as superoxide radical ($O_2^{.-}$), hydroxyl radical ($OH^.$), and singlet oxygen ($^1O_2$). ROS are highly toxic to vital cell constituents and are responsible for destruction of chlorophyll, DNA, membrane lipids and proteins. Formation of ROS is particularly prolific when absorption of light energy exceeds the capacity of photosynthetic electrons to transport it. Environmental stress factors diminish photosynthetic electron transport and CO_2 fixation at various stages of the photosynthesis process (Fig. 2). Therefore, a combination of an environmental stress with high light intensity may induce severe photo-oxidative damage to chloroplasts, and consequently cause decreases in the yield capacity of plants. The mineral nutritional status of plants greatly influences photosynthesis electron transport and CO_2 fixation in various ways (Marschner, 1995; Cakmak and Engels, 1999; Mengel and Kirkby, 2001). Impairment of the mineral nutrition of plants can, therefore, be accompanied by an enhanced potential for photo-oxidative damage, and this threat can be especially serious when plants are simultaneously exposed to an environmental stress.

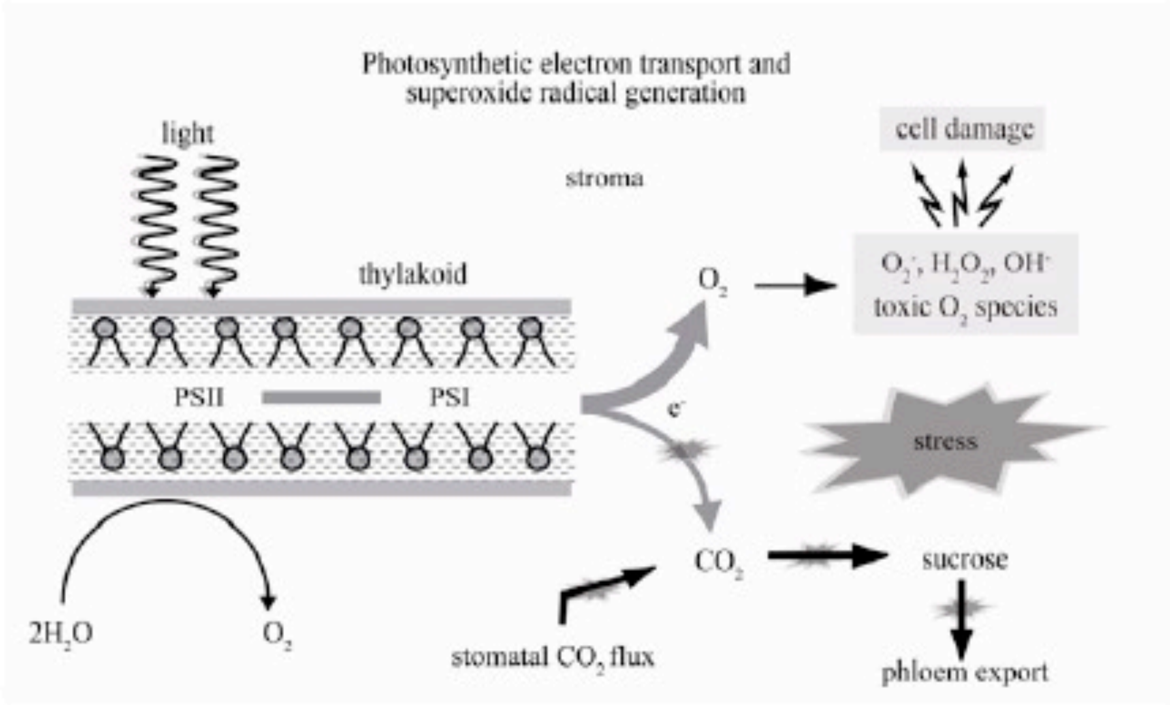

Fig. 2. Schematic representation of ROS formation in chloroplasts under environmental stress conditions.: indicates inhibition of the corresponding reaction by stress. (Cakmak, 2003, 2005).

Nitrogen

Of the mineral nutrients, nitrogen plays a major role in utilization of absorbed light energy and photosynthetic carbon metabolism (Kato et al., 2003; Huang et al., 2004). An excess of non-utilized light energy can be expected to occur in N-deficient leaves, where it leads to a high risk of photo-oxidative damage. In rice plants under high light intensity, N deficiency is associated with enhanced lipid peroxidation (Huang et al., 2004), and Kato et al. (2003) recently showed that plants grown under high-intensity light with a high N supply had greater tolerance to photo-oxidative damage and higher photosynthesis capacity than those grown under similar high light with a low N supply. Utilization of the absorbed light energy in electron transport was also much higher in N-adequate than in N-deficient plants. These results indicate that N-adequate plants are able to tolerate excess light by maintaining photosynthesis at high rates and developing protective mechanisms. To avoid the occurrence of photo-oxidative damage in response to excess light energy, the thylakoid membranes have a protective mechanism by which excess energy is dissipated as heat. Dissipation of excess light energy is associated with enhanced formation of the xanthophyll pigment zeaxanthin, which is synthesized from violaxanthin in the light-dependent xanthophyll cycle (Demmig-Adams and Adams, 1992, 1996):

$$\boxed{\text{Violaxanthin}} \underset{\text{low light}}{\overset{\text{high light}}{\rightleftharpoons}} \boxed{\text{Antheraxanthin}} \underset{\text{low light}}{\overset{\text{high light}}{\rightleftharpoons}} \boxed{\text{Zeaxanthin}}$$

In plants suffering from N deficiency, the conversion of xanthophyll cycle pigments and formation of zeaxanthin were enhanced, and were accompanied by chlorophyll bleaching, particularly under high light intensity (Verhoeven et al., 1997; Kato et al., 2003). In spinach, N-deficient plants dissipate a greater fraction of the absorbed light energy than N-adequate ones: up to 64% and only 36%, respectively. This difference was associated with corresponding changes in xanthophyll cycle pigments: about 65% of the total xanthophyll pigments were present as zeaxanthin and antheraxanthin in N-deficient plants compared with 18% in the N-adequate plants (Verhoeven et al., 1997). These results indicate impaired use of the absorbed light energy in photosynthetic fixation of CO_2, with consequently enhanced demand for protection against excess light energy, in N-deficient plants. Certainly, the reduction in the utilization of light energy and the consequently elevated need for protection against photo-oxidative damage in N-deficient plants can be more marked when the N deficiency stress is combined with an environmental stress.

The form in which N is supplied affects plant tolerance to photodamage. The light-induced conversion of violaxanthin to zeaxanthin, as a means to dissipate excess light energy was found to be stronger in bean leaves supplied with nitrate than in those supplied with ammonium (Bendixen et al., 2001). In good agreement with these findings, Zhu et al. (2000) demonstrated that nitrate-grown bean plants had higher tolerance to photodamage than ammonium-grown ones. Under very high light intensity ammonium-grown plants had, therefore, higher levels of lipid peroxidation and higher contents of antioxidative enzymes.

Potassium, magnesium and zinc

Similarly to N deficiency, deficiencies of K, Mg and Zn also enhance the sensitivity of plants to photo-oxidative damage. When supplies of these nutrients are low, leaf symptoms of chlorosis and necrosis, and disturbances of plant growth become more severe when plants exposed to high light intensity (Marschner and Cakmak, 1989; Cakmak and Marschner, 1992; Cakmak et al., 1995; Polle, 1996).

Deficiencies of K and/or Mg cause marked decreases in photosynthetic C metabolism and utilization of fixed carbon (Marschner, 1995; Cakmak and Engels, 1999; Mengel and Kirkby, 2001). Consequently, their deficiencies cause massive accumulation of carbohydrates in source leaves, with consequent inhibition of photosynthetic C reduction (Fig. 3). Consistent with these changes in photosynthetic C metabolism, an excess of non-utilized light energy and photoelectrons is expected in K- and Mg-deficient plants, which leads to photoactivation of molecular O_2 and the occurrence of photo-oxidative damage (Fig. 2). This is the main reason why Mg- and K-deficient leaves are highly light sensitive. Partial shading of K- or Mg-deficient leaves delayed or eliminated the occurrence of leaf chlorosis and necrosis (Marschner and Cakmak, 1989; Cakmak, 1994). These observations strongly suggest that photo-oxidative damage to chloroplasts is a key process in the occurrence of leaf symptoms under conditions of Mg or K deficiency. In contrast to Mg and K deficiency, P deficiency had no effect on sucrose transport from source leaves, and there was no accumulation of photosynthates in leaves (Fig. 3). Leaf chlorosis, such as is found in K- and Mg-deficient plants, is not typical of P-deficient plants (Cakmak, 1994). Because of the distinct effects of Mg and K on photosynthetic carbon metabolism and on ROS formation in chloroplasts, photo-oxidative damage in plants grown under marginal conditions, such as drought, chilling and salinity can be exacerbated when the soil supply of Mg or K is low.

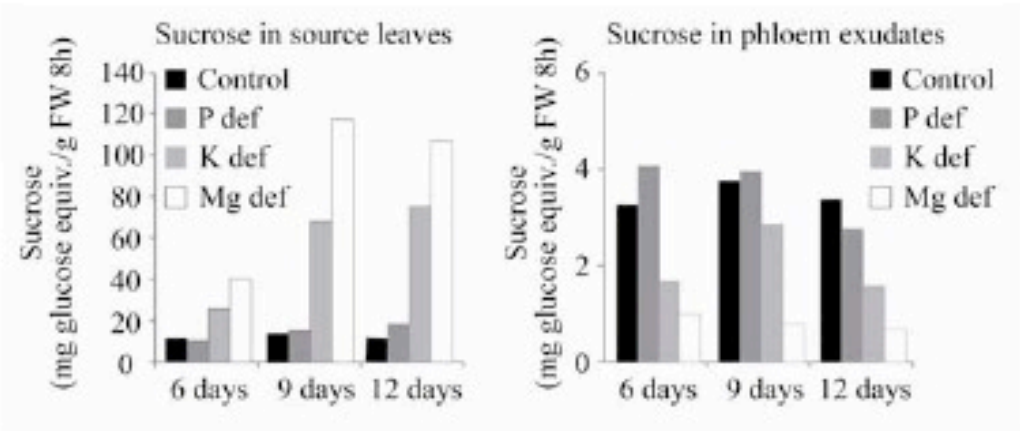

Fig. 3. Effect of insufficient supplies of P, K and Mg on sucrose concentration in source leaves, and on the export of sucrose from source leaves of bean plants via the phloem during 12 days of growth (Cakmak et al., 1994).

Salinity

Evidence is accumulating that reactive O_2 species are major mediators of salt-induced cell damage in crop plants. In several plant species, application of NaCl, even at low concentration, stimulated the activities of antioxidative

enzymes, which suggests a role of salt stress in ROS formation (Comba et al., 1998; Tsugane et al., 1999; Wang et al., 2005). On the basis of inhibitor studies and measurement of production of $O_{2.-}$ it has been shown that a plasma membrane-bound NADPH oxidase is involved in the generation of $O_{2.-}$ following salt treatments (Kawano et al., 2002; Aktas et al., 2005). Accordingly, salt stress-induced cell damage could be prevented by overexpression of superoxide dismutase (SOD) in chloroplasts of rice plants (Tanaka et al., 1999).

Zinc ions are known to be strong inhibitors of NADPH oxidase. In bean and cotton root cells Zn deficiency caused a significant increase in activity of NADPH-dependent $O_{2.-}$ production, and a resumed supply of Zn to Zn-deficient plants for 12 or 24 h caused a distinct reduction in the activity of $O_{2.-}$-generating enzymes (Cakmak and Marschner, 1988a; Pinton et al., 1994). Similarly, in tobacco cell cultures salt-induced $O_{2.-}$ generation by NADPH oxidase was strongly inhibited by Zn (Kawano et al., 2002). Previously, it has been often hypothesized that improving the Zn nutritional status of plants growing in saline conditions was critical for protection of plants against salt toxicity. This protective role of Zn was ascribed to its role in maintenance of the structural integrity of the plasma membrane and thus controlling the uptake of Na and other toxic ions (Welch et al., 1982; Cakmak and Marschner, 1988b). In light of the protective roles of Zn against ROS it can be suggested that Zn ions protect salt-stressed plants not only from uptake of toxic ions across plasma membranes but also from damaging attack of ROS.

Like Zn, K, too, is a critical mineral nutrient that protects plant cells from salt-induced cell damage. Impairment of the K nutritional status of plants by increased Na uptake is a well-known phenomenon (Liu and Zhu, 1997). The K/Na ratio is plant tissue is, therefore, considered to be a reliable indicator of the severity of salt stress, or for screening plant genotypes for high Na tolerance. In studies with Arabidopsis mutant lines Zhu et al. (1998) showed that mutant lines showing very high sensitivity to NaCl were also highly sensitive to low K supply, and exhibited a poor capacity for taking up K from a growth medium. As discussed above, salt stress represents an oxidative stress, and causes activation of $O_{2.-}$-generating NADPH oxidase. Recently, we found that K deficiency resulted in a remarkable increase in NADPH oxidase activity in bean, with concomitant production of $O_{2.-}$ (Cakmak, 2003, 2005). Shin and Schachtman (2004) also reported that ROS production was an early root response to K deficiency, which was catalysed by $O_{2.-}$-generating NADPH oxidase. These results suggest that salt stress-induced $O_{2.-}$ generation by NADPH oxidase could be aggravated by a lack of K. As Na toxicity causes K deficiency at cellular levels, the increase in NADPH-dependent $O_{2.-}$ generation under salt stress (Kawano et al., 2002) might be the result of an impaired K nutritional status of the plants. This point seems to be important, and should be elucidated in future studies.

Drought

In plants exposed to high light intensity at very low temperature or under drought stress, development of photo-oxidative damage and generation of ROS is very common (Foyer et al., 1997; Jiang and Zhang, 2002a, b; Wang et al., 2005). As discussed above, most mineral nutrients are a basic necessity for maintenance of photosynthetic electron transport. Therefore, the occurrence of photo-oxidative damage in plants stressed by drought or low temperature can be more dramatic when the plants also suffer nutrient deficiencies. Of the mineral nutrients, K plays a critical role in the stomatal activity and water relations of plants (Marschner, 1995; Mengel and Kirkby, 2001). Decreases in photosynthesis caused by drought stress in wheat become particularly high in plants growing under K deficiency, but are only minimal when the K supply is adequate. The capacity of plants to maintain high concentrations of K in their tissues seems to be a useful trait to take into account in breeding genotypes for high tolerance to drought stress. In Hibiscus rosa-sinensis plants grown under various K treatments, the root survival rate was strongly reduced when the water supply was limited, especially at the lowest K supply (Egilla et al., 2001); an adequate supply of K was essential for enhancing the drought resistance of the plants and improving their root longevity. The beneficial effect of an adequate K supply was ascribed to the role of K in retranslocation of photoassimilates in roots, which contributed to better root growth under drought stress (Egilla et al., 2001; Fig. 3).

As in salt-stressed plants, also in plants exposed to drought stress, ROS formation by $O_{2.-}$ -generating NADPH oxidase was enhanced (Zhao et al., 2001; Jiang and Zhang, 2002a, b). It appears that, in addition to ROS formation by photosynthetic electron transport, ROS production by NADPH oxidase activity is involved in cell damage and plant growth depression under drought stress. As indicated above, Zn and K strongly influence NADPH oxidation and NADPH-dependent $O_{2.-}$ generation. Under deficiency of these nutrients, especially of K, the capacity of root cells to oxidize NADPH is markedly increased, with concomitant production of $O_{2.-}$. In light of these results it may be suggested that the protective roles of Zn and K against drought stress seem also to be related to their inhibitory effects on NADPH-dependent $O_{2.-}$ generation. Therefore, in case of deficiency of these nutrients, plants become more sensitive to drought stress.

Chilling

Formation of ROS by NADPH oxidase and weakening of the antioxidative defensive systems are also important in chilling-induced cell damage (Shen et al., 2000; Aroca et al., 2005; Wang et al., 2005). Since insufficient supplies of K and Zn lead to significantly increased NADPH oxidase activity, ROS formation in plants grown at low temperatures can be additionally exacerbated under deficiencies of these nutrients. Production of ROS in chilling-stressed plants can also be expected, in parallel with impaired photosynthetic electron transport and CO_2 fixation (Wise and Naylor, 1987; Asada, 2000). There are several examples from field experiments that demonstrate a role of K and Zn in protection of plants under low-temperature conditions: frost damage and related decreases in potato plant yields were alleviated by application of large doses of K (Grewal and Singh, 1980); during winter, citrus trees were found to be more vulnerable to low temperatures and peroxidative damage when grown under Zn-deficient conditions (Cakmak et al., 1995). N, too, is involved in protection of plants against chilling stress; in studies with Eucalyptus seedlings it was found that seedlings with impaired N nutritional status were less susceptible to photo-oxidative damage in winter (Close et al., 2003). Like low N supply, also excess N results in high sensitivity to environmental stress: stress tolerance of plants can be diminished because of modified root and shoot growth. Marschner (1995) found that a very high supply of N often led to a reduced root-to-shoot ratio that, in turn, impaired the support of shoot biomass with mineral nutrients and water. Also, in plants receiving a high N supply, most parts of the roots may grow near to the soil surface, with consequently higher sensitivity to frost and drought damage (Gordon et al., 1999; Saebo et al., 2001). Saebo et al. (2001) showed that tolerance to frost damage was very low at the highest N supply rate, which led to the suggestion that the tissue N status should not be very high during winter.

Generally, plant genotypes that tolerate low-temperature stress are able to maintain high leaf water potential by closing their stomata and preventing transpirational water loss (Wilkinson et al., 2001). Calcium has been shown to be an essential requirement for chilling-induced stomatal closure in chilling-tolerant genotypes. Increasing the Ca supply induces stomatal closure, and this effect is most distinct in plants grown at low temperatures. It is also believed that ABA-induced induced stomatal closure is partially mediated by Ca released from internal guard cell stores or the apoplast (Wilkinson et al., 2001), and this function seems to make Ca a major contributing factor to chilling tolerance and protection of leaves from dehydration.

Conclusions

The existing data indicate that it is essential to improve the mineral nutritional status of plants under marginal environmental conditions, in order to sustain their survival and to maintain high yields. Plant requirements for mineral nutrients increase with increasing severity of the environmental stresses imposed by drought, heat, salinity, chilling, or intense light. Impairment of the mineral nutritional status of plants, therefore, exacerbates the adverse effects of environmental stress factors on plant performance. The present paper has focused on one of the major reasons for the aggravation of the adverse effects of stresses by an insufficient supply of mineral nutrients, namely, the enhanced production of highly toxic ROS and the resulting photo-oxidative damage to chloroplast pigments and lipids. The production of ROS during photosynthesis, which is normally an unavoidable process, is intensified because of the limited and diminished utilization of absorbed light energy in photosynthetic electron transport and CO_2 fixation, which results from environmental stresses such as drought, salinity and chilling. Mineral nutrients, such as N, K, Mg, Ca and Zn, supplied at adequate levels are an essential requirement for the maintenance of photosynthesis activities and utilization of light energy in CO_2 fixation. Therefore, the improvement of mineral nutrition of plants becomes a major contributing factor in protecting them from photo-oxidative damage under marginal environmental conditions. Further challenges include the gaining of better understanding of the roles of mineral nutrients in: i) ROS formation during photosynthesis and formation of plasma membrane-bound NADPH oxidase; ii) signaling pathways that affect the adaptive responses of plants to environmental stresses; and iii) expression and regulation of stress-induced genes that contribute to stress tolerance.

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Potential Development of Fertigation and its Effect on Fertilizer Use

Hillel Magen

International Potash Institute, Baumgärtlistrasse 17, CH-8810 Horgen, Switzerland. E-mail: ipi@ipipotash.org.

Abstract

Worldwide, the area of irrigated land has doubled impressively from 139 million ha in the 1960s to 276 million ha, i.e. ~20% of all arable land, in 2002. Of the irrigated land, 75% is in developing countries, which are thus enabled to produce more food for their growing populations, on the same land base. Because of this development, agricultural water withdrawal increased from 1,100 to 2,650 km^3 per year between 1950 and 1998-2002. Urbanization and improvement in the standard of living have led to rapid growth in domestic (municipal) and industrial water withdrawals, which have reached 40% of the global agricultural withdrawal.

Whereas 50% of the agricultural water withdrawal is consumed by plants (through evaporation and transpiration), up to 90% of the domestic and industrial water withdrawal is returned to rivers and aquifers, so creating a large potential source for the expansion of irrigation. However, only a limited proportion of this water is treated sufficiently to match the quality for agricultural usage, and full utilization of treated wastewater (TWW) might enable an increase of 10-70% in the total water drawn for agriculture.

The levels of nutrients found in TWW (typically 50, 30 and 35 ppm of N, P_2O_5 and K_2O, respectively) could supply a large proportion of the nutrient requirements of TWW-irrigated fields, and this needs to be reflected in fertilizer recommendations. Theoretically, full utilization of the output from conventional sewage treatment facilities could contribute 13.3, 8 and 9.3 million tonnes of N, P_2O_5 and K_2O, respectively, worldwide.

The development of fertigation is driven by water scarcity and the resulting introduction of localized irrigation, as well as by the environmental pressure to treat and dispose of TWW properly. The cultivation of vegetables and orchard fruits near megalopolises is an economically driven practice, which competes

strongly for potable water, but which also has high synergy with disposal of well treated municipal wastewater via localized irrigation.

A large-scale survey of plots irrigated with water from various sources, including TWW, showed that the available nutrients in TWW, especially phosphorus, must be taken into account when calculating fertilizer recommendations, nutrient balances and the selection of water emitters.

This paper describes the options and implications for increased fertigation using TWW.

Keywords: fertigation, nutrients, potassium, localized irrigation, treated wastewater, water withdrawal.

Introduction

Development of irrigation and potential of TWW

Worldwide, the irrigated land area has increased from 139 m hectares in the 1960s to 276 million ha in 2002; it now amounts to ~20% percent of all arable land (Fig. 1). In 2002, 75% of the irrigated land was in developing countries, which irrigation enabled to produce more food for their growing populations, on the same land base. Because of the expansion of irrigated land, the agricultural water withdrawal increased from 1,100 to 2,650 km^3 between 1950 and 1998-2002 (Table 1, Fig. 1). Urbanization and improvements in the standard of living have led to a parallel rapid growth in domestic and industrial water withdrawals, which now account for 30% of the global water withdrawal. Demand for water for non-agricultural uses is still increasing, in response to economic growth, rising populations and increased urbanization (FAO, 2004). Rosegrant et al. (2002) predicted that the absolute growth in non-agricultural demand for water would exceed that in agricultural demand, which would result in a reduction in agriculture's share of total water consumption in developing countries from 86% in 1995 to 76% in 2025 (FAO, 2004).

The increase in municipal water use, from 100 to 380 km^3 per year (Table 1, Fig. 1) is, however, of great potential value for agriculture: water from these sources is easily collected through sewage systems and can be treated to quality levels suitable for agricultural irrigation. An extreme example of the potential for municipal water use is found in Israel, where 95% of the population is connected to sewerage systems, 80% of the wastewater is treated in wastewater plants, and ~70% of the treated urban wastewater is used for agriculture (Icekson-Tal et al., 2003). Currently 30% of irrigation water used in Israel is

TWW, and in the near future this will increase to more than 50% (personal communication, J. Tarchitzky).

Table 1. Estimated global water withdrawal (km^3 per year and as percentages of total withdrawal).

Sector	1950 (1)	1995 (1)	1998-2002 (2)
	------------------------ km^3/year ------------------------		
Agriculture	1,1002,5002,650		
Percentage of total	796969		
Industries	200750776		
Percentage of total	142120		
Municipalities	100350380		
Percentage of total	7	10	10
Total	1,400	3,600	3,806

Source: (1)FAO, 2000. (2)Calculated from FAO AQUASTAT data base (http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm)

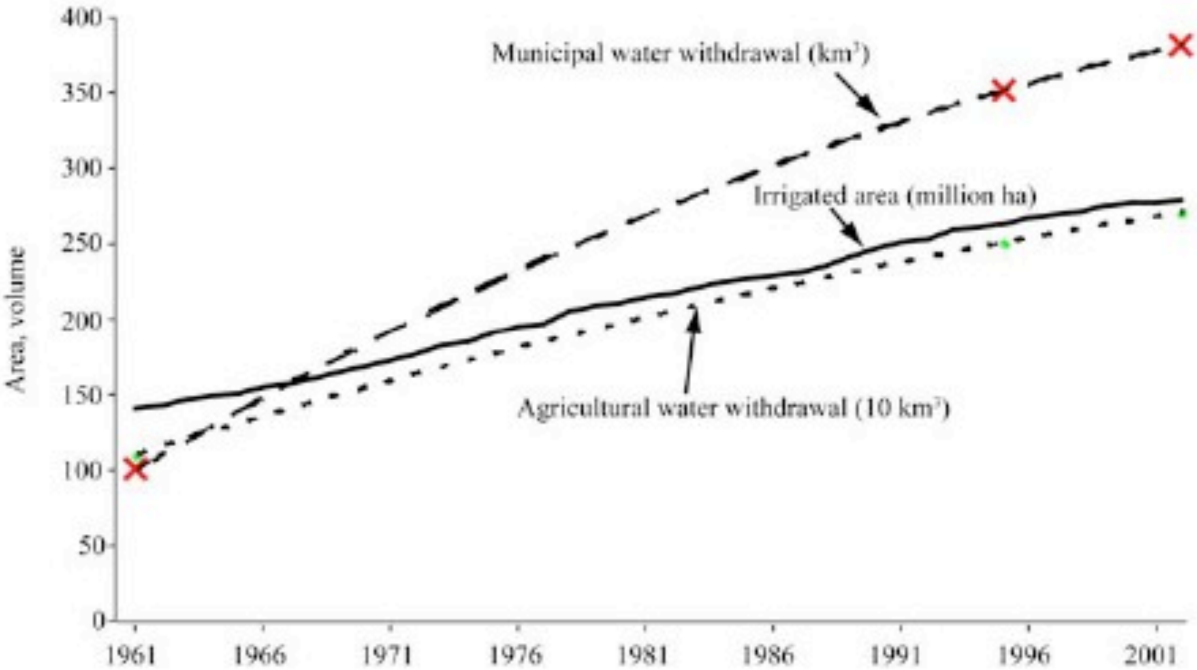

Fig. 1. Evolution of irrigated area, agricultural and municipal water withdrawal (1960 – 2003). Source: Area: FAO database; water withdrawal: FAO, 2000 (Crops and drops and FAO AQUASTAT).

In Asia, 84% of the water is used for irrigation, greater than the global share of 71% (Table 2). At the same time, the population in Asia consumes per capita only half of the global daily average (65 and 126 L/day per capita, respectively, Table 2). The demand for domestic water will increase significantly as both population and standard of living in the region rise, and thus the availability of wastewater for irrigation will also increase. For example, a city with a population of one million and water consumption of 200 L/day per capita would produce 62 million m^3 of wastewater per year, assuming that 85% flows into sewerage systems. Treated and supplied, this may be sufficient for the irrigation of 12,410 ha, or for production of 80,000 mt of grain.

Table 2. Annual water withdrawal and per capita consumption in Asia.

Region	Annual water withdrawal by sector [1]				Per capita consumption [2]	
	Agricultural		Domestic (municipal)		People (billion)	L/day
	km^3	% of total	km^3	% of total		
Asia	1,212.5	84	91.5	6	3,823	65
World	2,310	71	290.6	9	6,301	126
Asia as % of world	52.5		31.5		21.5	

Source:
(1)FAO AQUASTAT, http://www.fao.org/ag/agl/aglw/aquastat/regions/asia/index4.stm, data from 1996.
(2)Calculated from FAO FAOSTAT, http://faostat.fao.org/faostat/collections?version=ext&hasbulk=1&subset=agriculture, data from 2003.

Development of fertigation

The need to increase the efficient use of irrigation water is acute. The gap between the irrigation efficiency achieved in surface irrigation (25-40%) and that in pressurized localized irrigation (80-95%) justifies investment in the irrigation of marginal lands. The global area under sprinkler and micro-irrigation systems is estimated at 25 million ha, of which 40% are in the USA (ICID 2005), approximately 20% are under micro-irrigation. The USA, Spain, France, China, Italy and India each have over 1 million ha under sprinkler and micro-irrigation. In developed countries and those in arid and semi-arid regions, well over 80% of the irrigated land is under either sprinkler or micro-irrigation systems (ICID, 2005). The application of drip irrigation is expanding rapidly in India and China. In India the area under drip irrigation increased from about 1,000 ha in 1985 to 70,860 ha in 1991, mainly in Maharashtra (32,924 ha), Andhra Pradesh (11,585 ha) and Karnataka (11,412 ha). The drip-irrigated crops are mainly orchards (39,140 ha), but drip irrigation is also used for sugar cane (3,900 ha) and coconut (2,600 ha). The average cost of drip irrigation development ranges from US$750 to 2,000 per hectare. This fast growth can be partly attributed to the subsidies offered by the Government for the adoption of drip systems: a farmer can receive a subsidy up to US$750/ha (FAO, 1999). There are similar expansions occur in China, where the dependency on government subsidies is very high.

There are no exact figures to quantify the penetration and development of fertigation systems. However, it is commonly perceived that the shift to localized irrigation requires adaptation of the fertilization practices, mainly because of the smaller active root zone, lower content of available organic matter, and the different flow rates of water and nutrients required, compared with those associated with other irrigation systems (Scaife and Bar-Yosef, 1995; Hagin et al., 2002). Therefore, fertigation systems are to be found only in combination with pressurized irrigation systems, and mostly with localized systems, i.e., drip and other micro-jets, and mini-sprinklers.

Water scarcity for agriculture, together with large increases in water demand for municipal uses and the large investments in water treatment facilities that have been stimulated by environmental regulations, all create a significant source of water available for irrigation. Pathogenic viruses, bacteria, protozoa and helminths may be present in raw municipal wastewater, but after proper treatment do not pose any risk (Asano, 1989). In practice, the use of localized irrigation significantly lowers health risks as the water does not come into direct contact with the crop and the field workers, especially in drip and sub-soil drip systems.

Discussion

Value of nutrients in TWW

Even though irrigated land forms only 17% of global cropland, it provides 40% of global food production (FAO, 2000). If we assume that the amounts of nutrients supplied support a proportional amount food production, we can estimate that approximately 60 million tonnes of nutrients (40% of global nutrient consumption) are applied via irrigated agriculture. Similarly, we can estimate that the total amount of crop nutrients applied to land equipped with pressurized irrigation (25 million ha; ICID 2005) is in the order of 6 million tonnes, and that the amount applied via micro-irrigation (to approximately 4.5 million ha) is some 1.5 million tonnes, assumed to be applied mostly via fertigation.

How much of these nutrients is there in all domestic wastewater, worldwide? Theoretically, by multiplying the average concentrations of N, P and K in domestic wastewater, which are 50, 10 and 30 ppm, respectively (FAO, 2002), by the amount of municipal water withdrawal (380 km^3), and an efficiency factor of 0.7, we estimate that the total amounts of nutrients available are 13.3, 8.0 and 9.3 million tonnes of N, P_2O_5 and K_2O, respectively. These amounts are very significant, especially for potassium, for which this amount is approximately 35% of the global market.

Thus, the average contributions of nutrients from irrigation with TWW, assuming an annual application rate of 5000 m^3/ha, would be 250, 114 and 180 kg/ha of N, P_2O_5 and K_2O (FAO, 2002). A World Bank study estimated that the fertilizer value of nutrients (N, P and K) in treated municipal effluents was worth about 3 cent/m^3, which reflects a potential annual saving to the farmer of $130/ha in fertilizer costs (Hamoda, 2004). A similar calculation, based on data from Israel (Israel Ministry of Agriculture, 2004), shows that the total amounts of N, P_2O_5 and K_2O can reach 220, 30, and 290 kg/ha, respectively (Fig. 2), worth approximately $200/ha ($100, 30 and 75 for N, P and K, as urea, TSP and KCl, respectively). The value of nutrients in TWW can vary greatly, depending on the water source and treatment (Fig. 2). Cornel and Weber (2004) calculated that typical irrigation at 5,500 m^3/ha with TWW containing 50-54 and 7-8 ppm of available N and P, respectively, results in the application of N and P at 285 and 43 kg/ha, respectively; far more than is required by some summer crops in Germany.

The contribution of the nutrients in TWW is thus significant and plays a role in the decisions made by farmers. However, the balance may not be optimal, and the data indicate, especially, excessive P supply.

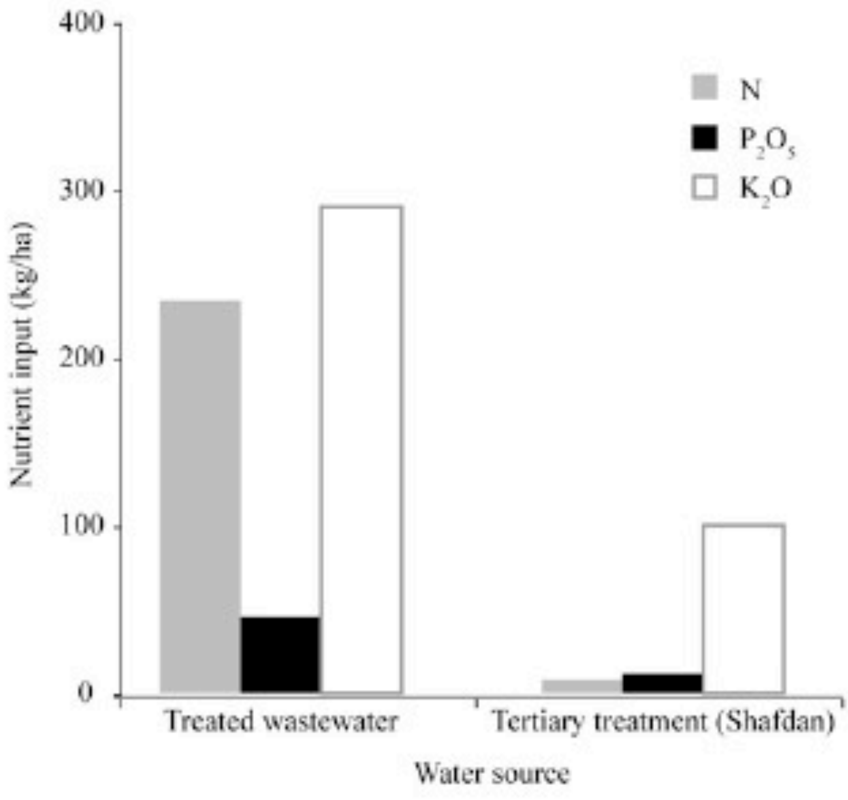

Fig. 2. Contributions of N, P_2O_5 and K_2O (kg/ha) from two sources of wastewater at standard irrigation rates. Source: Israel Ministry of Agriculture, 2004.

Management of nutrients in TWW

Available nutrients in TWW are supplied at constant rates according to crop water requirements. However, this may lead to nutrient deficiencies at times when water requirements are relatively low, and vice versa. For example, a citrus orchard will require a high dose of phosphate in the spring and no nitrogen application later than a certain stage of fruit development. Cornel and Weber (2004) concluded that, depending on climate, plant, soil, and irrigation system, it is possible to satisfy a significant part of, if not the whole fertilizer demand by using TWW for irrigation.

Nitrogen in TWW is found in various forms (organic, as nitrate, and as ammonium), depending on the type of treatment undergone by the effluent. Phosphate is found as both orthophosphate and as inositol hexaphosphate (IHP), and potassium as cation K^+. Typical nutrient concentrations in various water sources are presented in Table 3. The various treatment processes affect the concentrations and ion types of N and P, whereas K concentrations in the outflow mostly reflect those at the inflow.

Table 3. Typical nutrient concentrations (ppm) in TWW (from various sources).

Water source	Typical domestic waste water	Secondary treatment before SAT (1)	Secondary treatment before SAT (1)	Tertiary treatment	Filtered effluent	Secondary treatment
	-- ppm --					
Nitrogen (total as N)	85					
NH_4-N		7	<0.02	0.55		30-60
NO_3-N		0.28	9.34	7.74	0.08-20.6	
Phosphorus (as P)	20	2.2	<0.05	1.6	3.8-14.6	6-15
Potassium (as K)		18	24	15.5	13-31.2	30-120
Source (reference)	FAO 2002	Icekson -Tal et al., 2003	Icekson -Tal et al., 2003	Gori et al., 2004	Asano, 1989	Israel Min. of Agr., 2004

(1) SAT: Soil Aquifer Treatment

Nutrient supply from TWW

The nutrient inputs from regular fertilization practices and those from TWW were compared at more than 130 plots in various locations in Israel during 2001-2003 (Israel Ministry of Agriculture, 2004). The fertilization practices were similar irrespective of which of three types of water was used: well (ground) water; secondary treatment wastewater; and water from tertiary treatment with SAT. As shown in Fig. 3, both TWW sources contributed significant amounts of N, P and K, but the inputs from the tertiary treatment were lower, especially for N. One of the conclusions to be drawn from the survey is that farmers' practices must include a calculation of the nutrient contribution from the water source, especially that of P, since its contribution from TWW is far larger than the crop requirement (Fig. 3), and this excess could accumulate after a relatively short period of time.

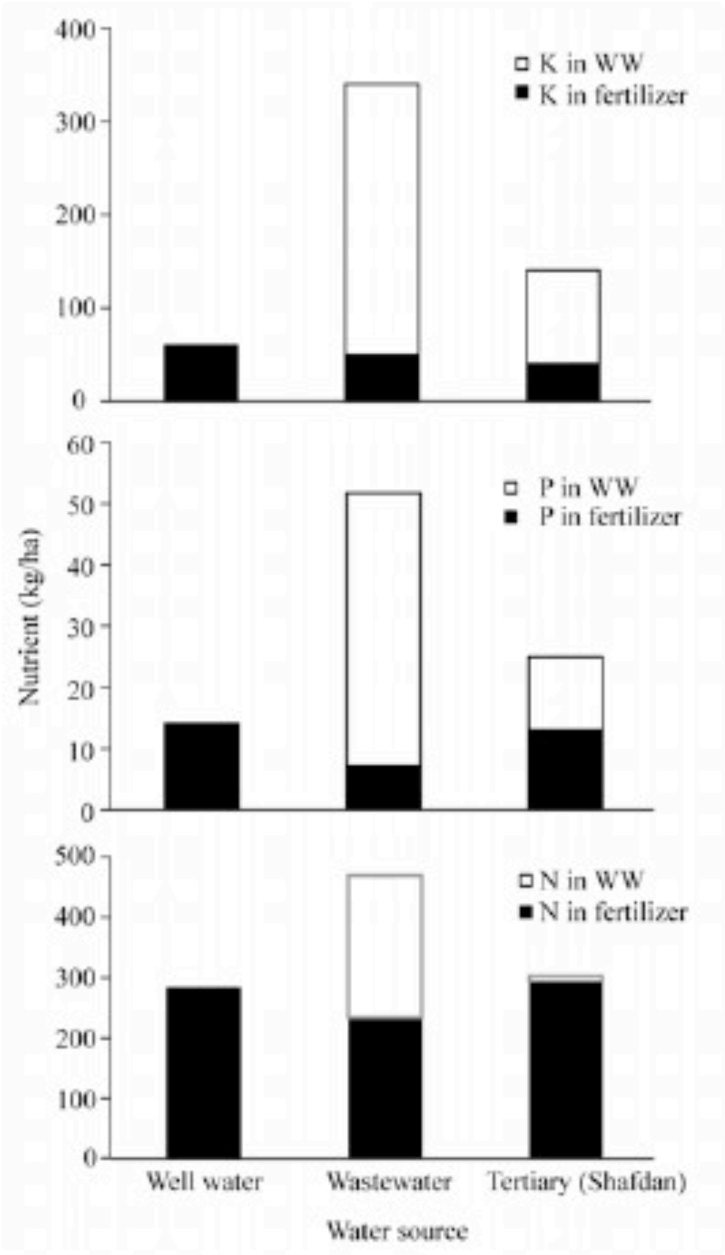

Fig. 3. Average inputs of N, P_2O_5 and K_2O (kg/ha) from both mineral fertilizers (in black) and three water sources at standard irrigation levels. Source: Israel Ministry of Agriculture, 2004.

Accumulation of N, P and K in the soil profile was also studied in this survey. As shown in Fig. 4, under irrigation with TWW (ww1 and ww2), P was highly accumulated in the soil profile down to 60 cm (2.5-4.7 ppm in saturated paste). In contrast, under regular fertilization and irrigation with well water (fw1) only 0.8 ppm of P (in saturated paste) was found at -30 cm.

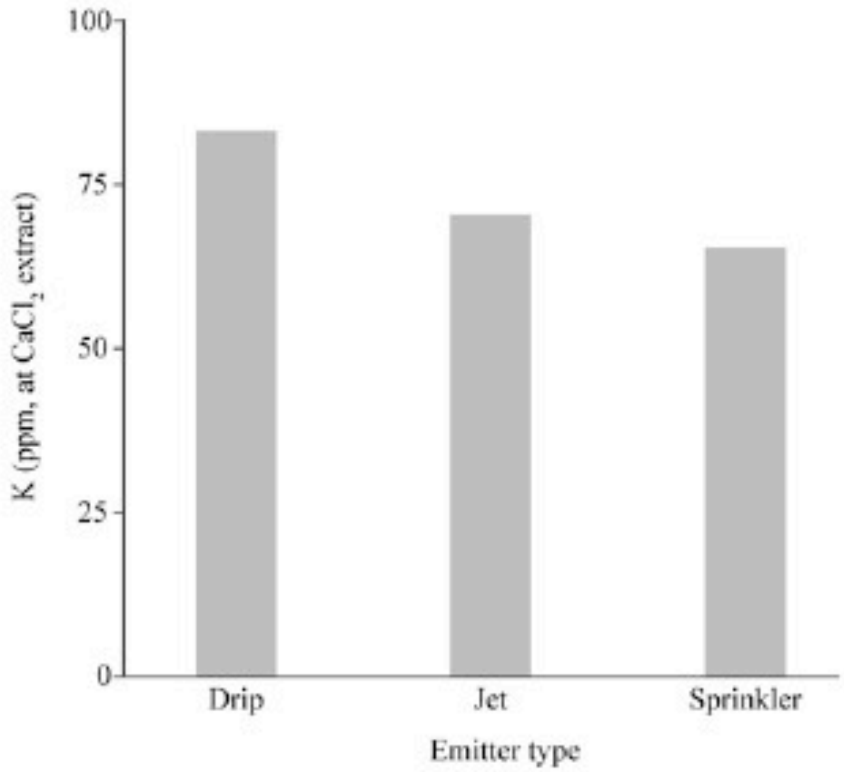

Fig. 4. P concentration in soil profile under irrigation from various water sources (ppm in saturated paste). Source: Israel Ministry of Agriculture, 2004.

The effect of different irrigation emitters on the nutrient concentration found in the soil and in the leaves of fruit trees grown in the surveyed plots was also investigated. The results show that for potassium there was an inverse response to the wetted area: the smallest wetted area (drip) corresponded to the highest K level in the soil solution in the 0 to 120 cm soil layer (Fig. 5) and in the leaves of the citrus and avocado trees tested (data not shown): the K concentration in saturated paste reached 82 ppm under the wetted area of the drippers, but only 65 ppm under the sprinklers. In the 130-plot survey the nutrient whose behavior was most clearly affected by the water emitter type was K. This implies that consideration must be given not only to the concentration of nutrients in the TWW, but also to the type of emitter used.

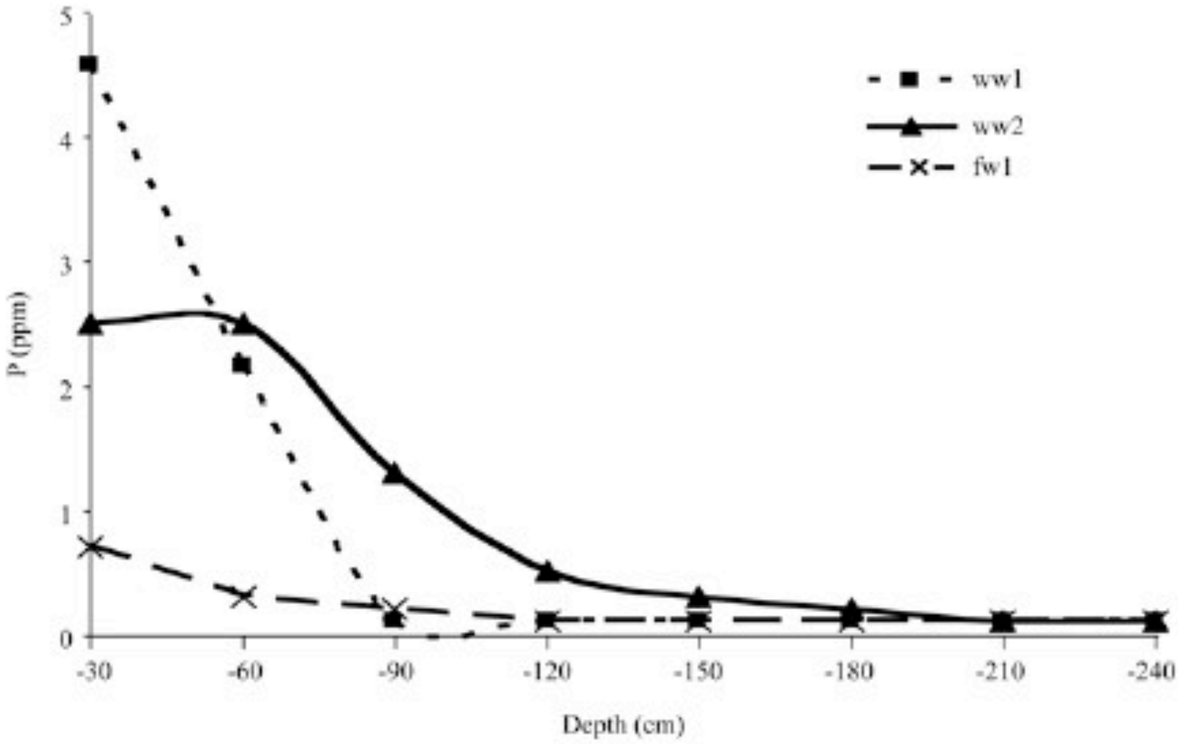

Fig. 5. K concentration (ppm, $CaCl_2$ extraction) in saturated paste of wetted area under drip, jet and sprinkler irrigation. Source: Israel Ministry of Agriculture, 2004.

Conclusions

Water scarcity and increased municipal water use are the main drivers for large-scale development of pressurized, localized irrigation systems, whose development will, in turn, stimulate the development of fertigation. Use of TWW in fertigation systems offers several advantages, including the value of the nutrients already present in the water, and may offer significant cost savings of US$100-200/ha, depending on the water quality. But whereas typical N and K levels in TWW already match plant demands, typical phosphate levels in TWW-irrigated plots cause high levels of P at various soil depths, which suggests that P is very mobile in soil profiles under such conditions, so that an excess concentration easily can be reached. In the future fertigation may closely linked to TWW irrigation, and the management of the system will need to address the nutrients as well as the soil and irrigation.

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Role of Fertigation in Horticultural Crops: Citrus

Ashok K. Alva

USDA - Agricultural Research Service, Vegetable and Forage Crop Research Unit, 24106 North Bunn Road, Prosser, WA 99350, USA.
E-mail: aalva@pars.ars.usda.gov; website: http://www.ars.usda.gov/pwa/prosser.

Abstract

Advances in micro-irrigation techniques, e.g., drip and under-tree sprinklers, have facilitated more widespread adoption of fertigation, especially for perennial crops, including citrus. It is generally believed that fertigation improves nutrient uptake efficiency and, therefore, is preferable to dry fertilizer broadcast application because it increases the yield, enhances crop quality, and minimizes loss of nutrients, i.e., leaching of NO_3-N below the root zone. The evaluation of tree response to changes in nutrient management requires long-term studies because of the large nutrient reserves in the woody portion of the tree. In this paper we have summarized recent evaluations of fertigation for citrus. Two-year studies on newly planted citrus trees revealed no significant difference between the fertigation and dry fertilizer broadcast treatments, partly because of the very low nutrient demand during at least 2 years after planting. Evaluation of 7- and 8-year-old trees that had grown under various nutrient management programs since planting revealed significantly greater yields of both fruit and total soluble solids from those under fertigation than from those under dry granular fertilizer broadcast management. The optimum N rate with continuous fertigation treatment was lower by 35 kg/ha than that in the dry fertilizer broadcast treatment. A 6-year study on over-20-year-old "Hamlin" orange trees on "Cleopatra mandarin" rootstock found no significant difference between the fertigation and dry fertilizer broadcast treatments. A 5-year study on over-35-year-old "Valencia" orange trees on "Rough Lemon" rootstock found a significantly lower surficial aquifer NO_3-N concentration under the trees that received total fertigation than under those that received dry granular broadcast applications three times per year at similar N rates. The groundwater NO_3-N concentrations in the former were below the maximum contaminant limit (MCL) of 10 mg/L whereas those of the latter were above it throughout the study.

Introduction

"Fertigation" is a technique for application of fertilizers in the irrigation water. The advantages of fertigation include (Burt et al., 1998): (i) minimizing soil compaction by avoiding heavy equipment traffic through the field to apply fertilizers; (ii) reduced energy demand; (iii) reduced labor input; (iv) careful regulation and monitoring of nutrient supply; (v) even distribution of nutrients throughout the root zone; and (vi) application of nutrients matched in amounts and timing to the plant nutrient requirements. Fertigation can be applied through buried or surface drip-lines or through sprinklers. Recent technological developments in the drip and micro-irrigation methods have accelerated the adoption of fertigation for a wider range of crops, including fruit trees. Uniform distribution of water by a given injection system is important for maximizing the uniformity of distribution of nutrients delivered through fertigation. Managing irrigation to minimize the leaching of water below the crop rooting depth is critical to minimizing their leaching below the root zone. It is generally believed that carefully managed fertigation results in lower nutrient leaching losses than broadcast application of water-soluble granular fertilizers. However, this is dependent on the ability of the crop to take up a large amount of nutrients immediately following their application, and subsequently to redistribute them from the vegetative crop parts into those of economic importance, i.e., fruits, tubers, etc.

The major objective of this paper is to summarize the recent advances in fertigation of horticultural crops, with particular emphasis on irrigated citrus orchards. Evaluation of the response of citrus trees to changes in nutrient management requires long-term studies, because of the large nutrient storage capacity of the woody portion of the trees. The response of citrus trees to fertigation could vary depending on: the growth parameters of young non-bearing trees; fruit yield response; leaf nutritional status; or orange vs. grapefruit response. Unfortunately, despite the adoption of fertigation a number of years ago, there have been rather few long-term response evaluation studies. The available studies and unpublished data are summarized in this paper, despite their often conflicting findings. Since this is a review paper, no "Materials and Methods" section is necessary. Some background information on each of the reviewed studies is presented in the "Results and Discussion" section.

Results and discussion

Young tree growth

Willis and Davis (1991) conducted a study in Florida, using “Hamlin” orange trees on “Sour Orange” rootstock grown in a Kanapaha fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleaquults). They evaluated two N rates (0.06 and 0.11 kg/yr per tree), applied either as dry granular source broadcast, five times per year, or as fertigation at 5, 10, or 30 applications per year. Part of the results are shown in Fig. 1. The tree growth response was not significantly influenced by either the method of N application or the frequency of fertigations at either N rate. The authors concluded, despite the lack of demonstrated beneficial effects of fertigation based on one year’s tree growth data, that additional years of response measurements were needed to evaluate the difference between the effects of fertigation and broadcast application (at lower frequencies) of dry granular fertilizers.

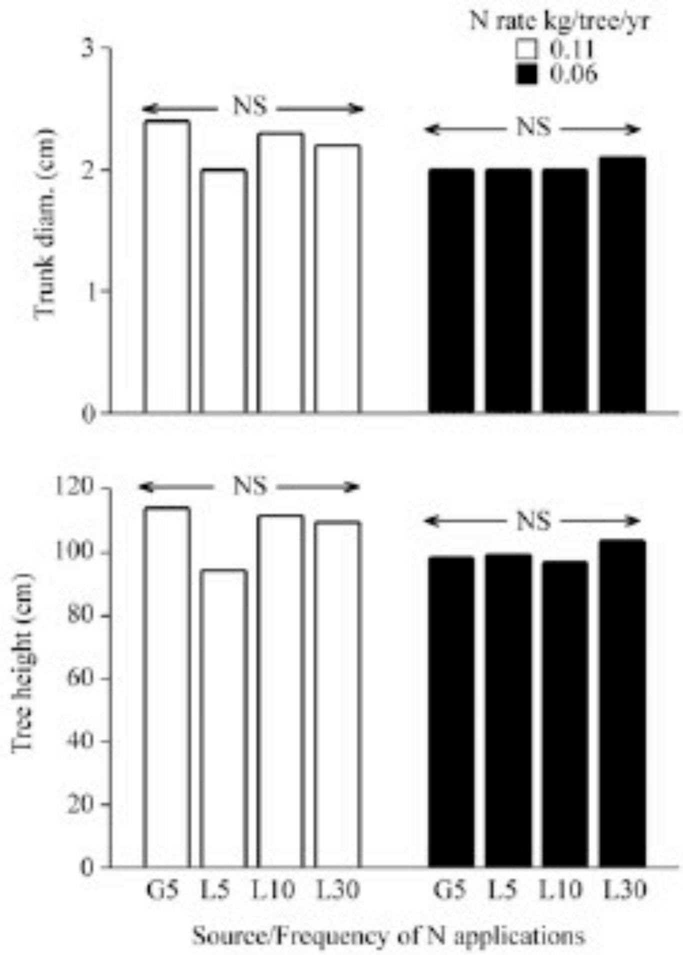

Fig. 1. Growth responses of “Hamlin” orange trees on “Sour orange” rootstock at two N rates, as broadcast application of dry granular fertilizer and via fertigation (extracted from Willis and Davis, 1991).

Young bearing trees

Thompson et al. (2002) conducted field studies on 5-year old "Newhall" navel orange trees on "Carrizo" citrange rootstock growing on a Gilman loam soil in Maricopa County, Arizona. The trees were planted in 1997 and the second year treatments included a factorial combination of three N rates (68, 136, and 204 g/yr per tree) and three application frequencies; either weekly (27 appl.), monthly (7 appl.) or three applications during the growing season. Increasing N rates increased the leaf N concentration significantly, particularly at the N rates of 136 and 204 g/tree, compared with that of the unfertilized trees. The weekly application of N at either 68 or 136 g/yr per tree significantly increased the fruit yield compared with that of the unfertilized trees. The responses of the trunk diameter, leaf N and fruit yield of 2-yr-old trees were non-significant across a wide range of N application frequencies (3 to 27/yr) (Fig. 2). In a parallel study (Weinert et al., 2002) reported that only 25% of fertilizer N was taken up by the trees, therefore, the lack of response to N rates and/or frequency of application was not unexpected.

Stored N in the nursery trees plays a major role in providing N nutrition of the trees during 1-2 years after planting. Accordingly, even for young trees, the evaluation of the effects of N rate/frequency should be carried out for several years to enable valid conclusions.

On the basis of the two studies described above and that of Rasmussen and Smith (1961), it appears that neither the choice of fertilizer delivery method (fertigation vs. dry granular-broadcast) nor the frequency of fertigation had any significant effects on the tree growth and leaf N concentrations during 1- to 2-year evaluations following planting. This lack of response was related to redistribution of stored nutrients in the trees, which leads to a very small portion of the applied nutrients being taken up by the young trees.

Schumann et al. (2003) presented the response data from 2 years of observation of 7- and 8-year-old trees, during the comparative evaluation of water-soluble granular (WSG; four equal applications per year), fertigation (FRT; 15 applications per year), and controlled-release fertilizer (CRF; single application per year) on over-7-year-old trees. These treatments were established at the time of planting, and the ranges of N rates were adjusted to match tree growth. Therefore, the trees were exposed to several different N sources and rates during the entire growth period prior to the yield evaluations, which were done during the 7th and 8th years. The N rates evaluated were 78, 134, 190, and 246 kg/ha/yr. The results showed quadratic responses to N rates for canopy volume, fruit yield, fruit numbers, juice yield, and soluble solids yield (Fig. 3). At the optimal N rates, the peak fruit yield was 20 Mg/ha for the WSG source, whereas it was close to 25 Mg/ha for the FRT source. The net return to the growers is based on the yield of soluble solids, and by this criterion the optimal N rates were 145 and 180 kg/ha for the fertigation and dry granular broadcast treatments, respectively. Thus, there was an N saving of about 35 kg/ha in the fertigation treatment, which resulted in about 0.35 Mg/ha increased yield of soluble solids compared with that from the trees that received dry granular broadcast application of fertilizer. This study demonstrated for the first time the distinct benefits (increased yield at lower optimal N rate) of fertigation, by conditioning the trees to different sources of fertilization over a long period of time.

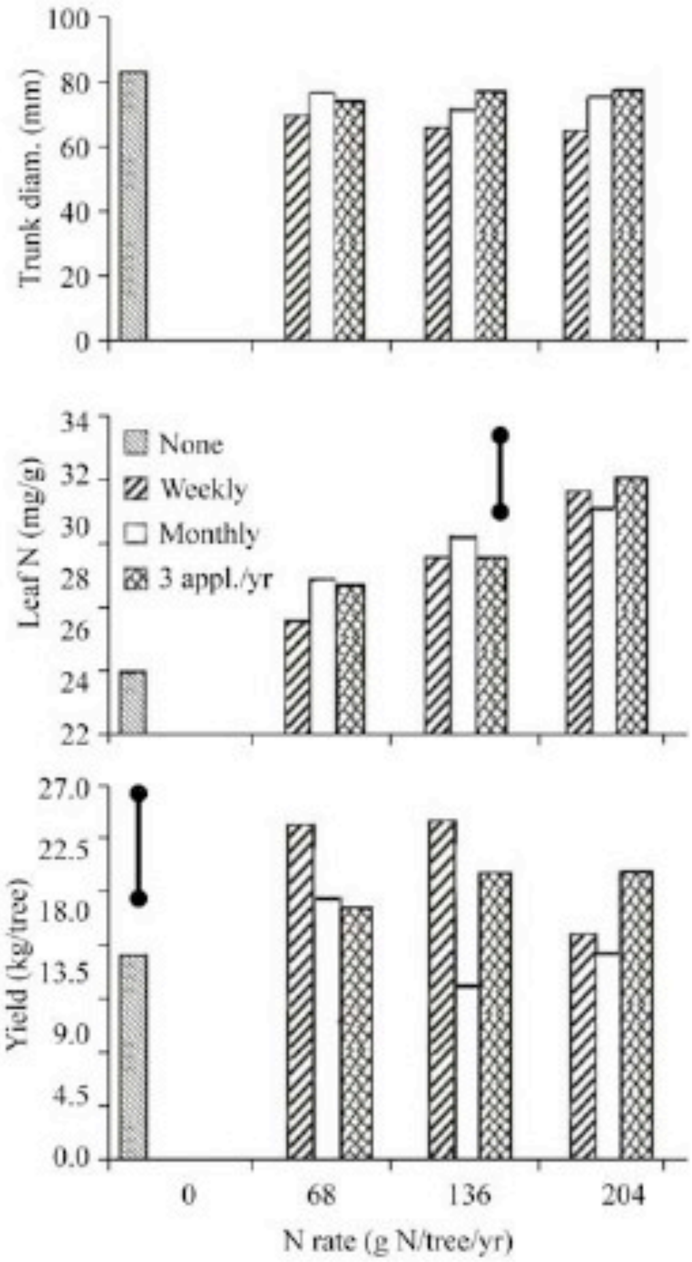

Fig. 2. Trunk diameter, leaf N and fruit yield of 2-year-old "Newhall" navel orange trees on "Carrizo" citrange rootstock, as influenced by different N application rates and fertigation frequencies (extracted from Thompson et al., 2002).

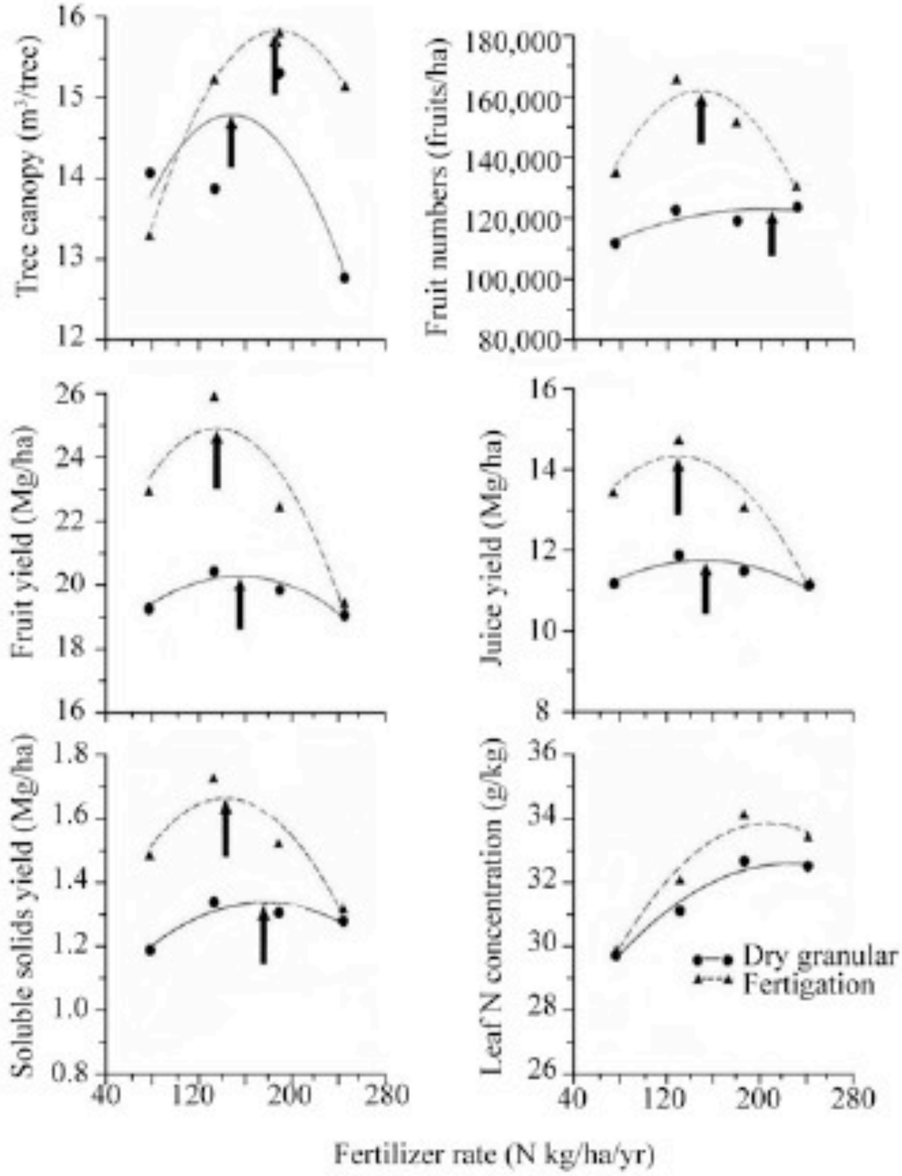

Fig.3. Effects of fertilizer sources and rates on tree growth, yield and leaf N concentration responses of 7- and 8-year-old "Hamlin" orange trees on "Swingle" citrumelo rootstock grown on a Candler find sand in Florida (extracted from Schumann et al., 2003). Yield response data are cumulative for the years 7 and 8.

Schumann et al. (2003) conducted a parallel study to compare three sprinkler coverage areas, comprising circles of 1.5, 3.0 or 4.5 m diameter around each tree. All sprinklers delivered water at 37.8 L/h, regardless of the coverage area, and two N rates – 134 and 190 kg/ha delivered as fertigation (15 applications/yr), were evaluated. At the higher N rate, the yields of soluble solids and juice increased with increasing area of sprinkler coverage, over the full range. At the lower N rate, the responses followed a quadratic curve, with decreases in both soluble solids and juice yields at the largest sprinkler coverage area. This study demonstrated that by conditioning the root distribution to different sprinkler coverage areas over the entire 8-year growth period of the trees, the response of the soluble solids yield to sprinkler coverage area differed with different N rates.

Mature Bearing Trees

A 6-year field experiment was conducted in central Florida, with over-25-year-old “Hamlin” orange trees on “Cleopatra mandarin” rootstock, planted at 286 trees/ha in a Tavares fine sand (hyperthermic, uncoated Typic Quartzipsamments), to evaluate the effects of various rates and sources of fertilizers on fruit yield and quality, and on the fate and “transport” of N in the soil (Alva and Paramasivam, 1998; Alva et al., 2005). Fig. 4 shows responses of the 3-year mean fruit yield to applications of N and K at rates of 112 to 336 kg/ha/yr as a water-soluble granular source (four applications/yr) or of 112 to 280 kg/ha as fertigation (18 applications/yr). Across the full range of N rates – 112 to 336 kg/ha – the fruit yield response was quadratic with the optimal N rate at about 260 kg/ha. At a given N rate, fruit yield was not significantly different between the treatments which received either dry granular or fertigation sources. According to the findings of this study regarding the fruit yield response, fertigation failed to demonstrate a significant advantage over the WSG broadcast application.

Alva et al. (1998; 2003) conducted a demonstration project in two identical 32 ha blocks of over-34-year-old “Valencia” orange trees on “Rough lemon” rootstock, planted at 286 trees/ha in an Astatula fine sand in Highlands County, Florida. Both blocks were irrigated via-under-the tree, low-volume sprinklers, with one emitter per tree delivering 96 L/hr into a wetting area of 28 m^2 per tree. During 1993 and 1994, both blocks were under similar management regimes, including fertilizer application at N rates of 197 and 209 kg/ha, respectively. Dry granular sources of N, P, and K were used with the annual rates split among three broadcast applications: Jan./Feb., May/June, and Sept./Oct. Subsequently, for 4 years the two blocks received differing fertilizer treatments, whereas all other management practices, including irrigation, were the same in the two blocks. The nitrogen rate was about 180 kg/ha for both blocks, but one block received a dry granular product that included P and K sources, in a 1.0:0.5:1.0 NPK blend, which was broadcast three times/yr (Jan/Feb, May, and Sep), whereas the second block received the same annual N rate except that the NPK blend was applied in 18 fertigations per year, in Jan.-May and Sept.-Oct. Because of heavy rainfall (60% of the total annual precipitation), no fertilizer was applied during June through August. The results showed that over a 4-year period the cumulative fruit yield was 11% greater and the total soluble solids

(TSS) yield was 16% greater with fertigation than with dry granular fertilizer application (Fig. 5). This was a demonstration project that used large commercial-size blocks to facilitate application of commercial industrial-scale management practices. Therefore, there were no replications, which limited the statistical analysis of the data.

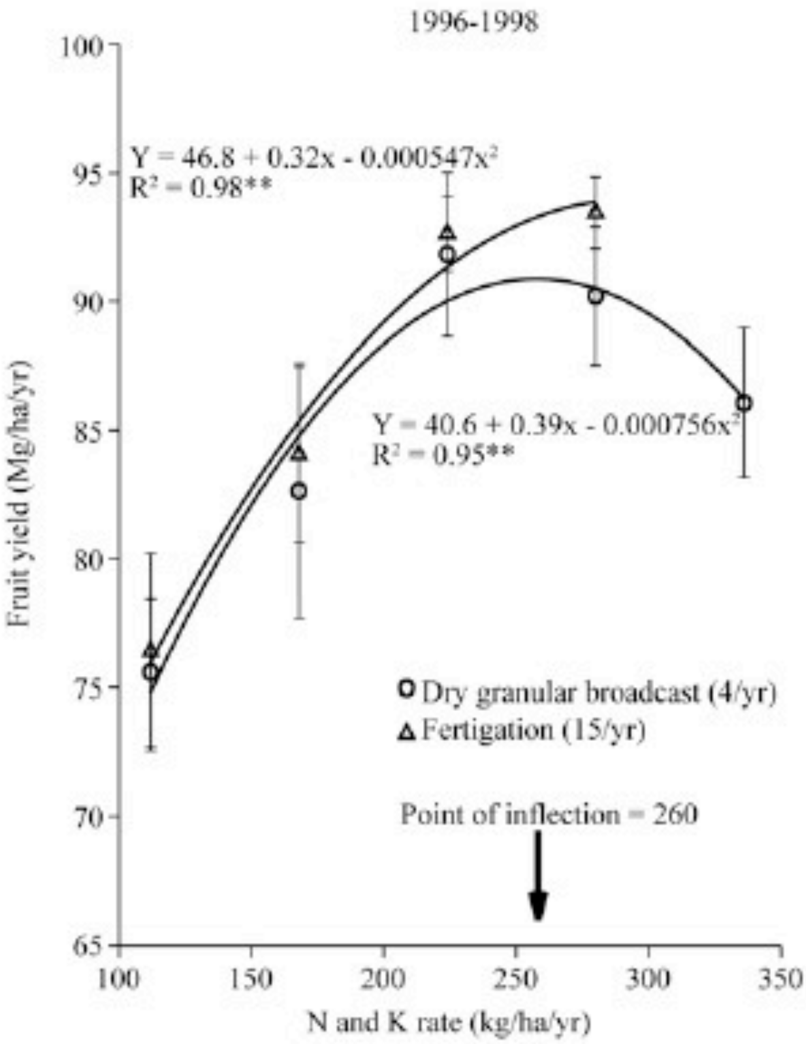

Fig. 4. Fruit yield responses of over-25-year-old "Hamlin" orange trees on "Cleopatra mandarin" rootstock, grown on a Tavares fine sand in Florida, to various rates of fertilizer, applied via broadcast application of water soluble granular (WSG) four times/yr or via fertigation (FRT) 18 times/yr. The data shown are mean values for years 4 through 6 of the study (extracted from Alva et al., 2005). Vertical line through each data point represents value of standard error of the mean.

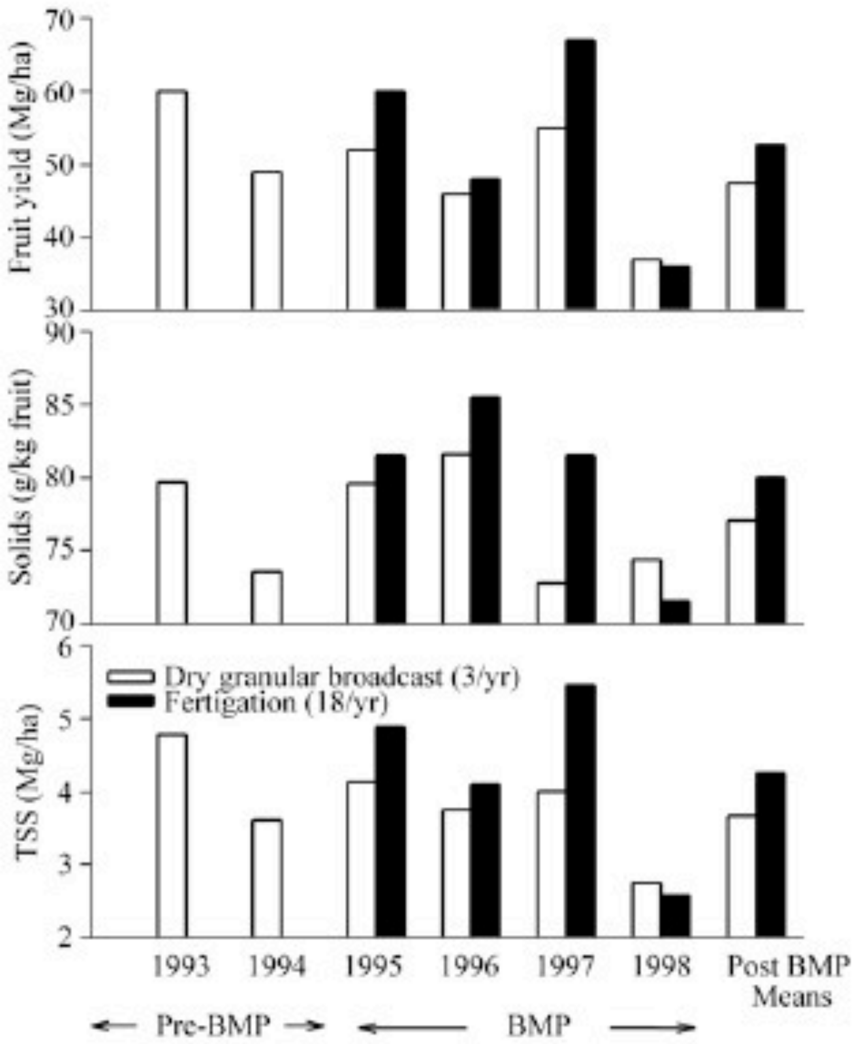

Fig. 5. Fruit yield and total soluble solids (TSS) responses of “Valencia” orange trees on “Rough lemon” rootstock subjected to dry granular broadcast or fertigation at similar N rates (extracted from Alva et al., 2003).

The NO_3-N concentration in the surficial aquifer was monitored during the study by sampling four monitoring wells in each block (Fig. 6). When the study began, the surficial aquifer NO_3-N concentration was above the maximum contaminant limit (MCL) of 10 mg/L in both the citrus orchards. As the study progressed, the NO_3-N concentration in the groundwater beneath the orchard that was under fertigation decreased to levels that were well below the 10 mg/L MCL, and also significantly lower than those in the groundwater underneath the orchard that received broadcast application of dry granular fertilizer. In the latter, the NO_3-N concentrations in the surficial aquifer generally remained above the 10 mg/L MCL. This long-term study demonstrated for the first time, the beneficial effects of fertigation in decreasing the NO_3-N leaching into the surficial aquifer underneath citrus groves in sandy soils exposed to high summer rainfall.

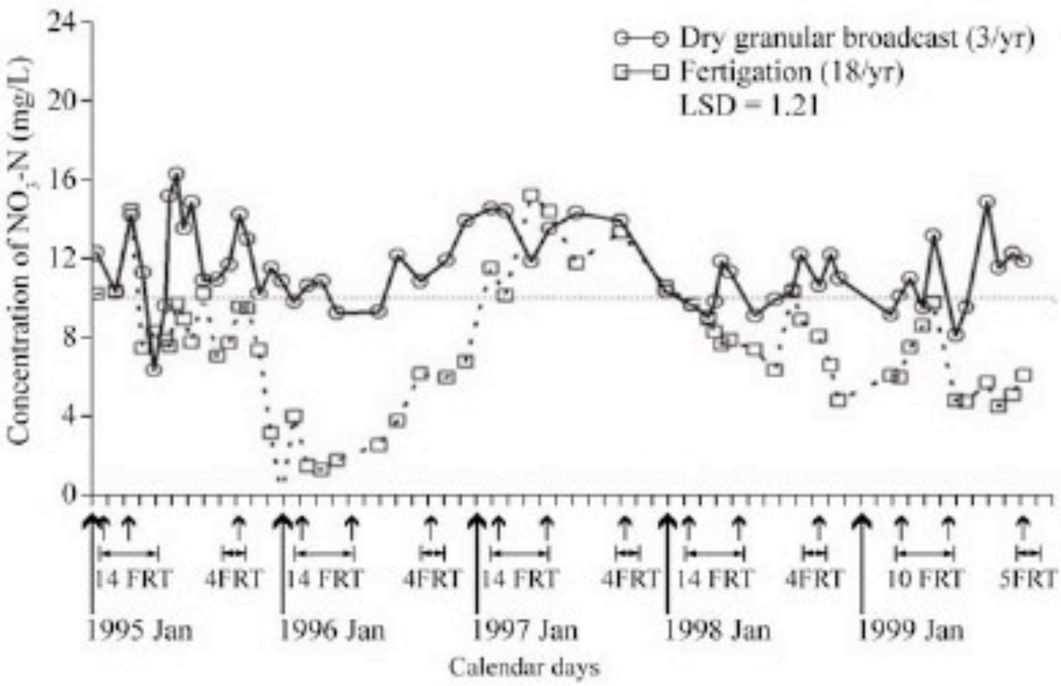

Fig. 6. Concentration of NO_3-N in the surficial aquifer underneath citrus groves with over-34-year-old “Valencia” orange trees on “Rough lemon” rootstock grown in Astatula fine sand in central Florida. Each data point is the mean of the data from four monitoring well samples (A.K. Alva 2005, unpublished data).

Dasberg et al. (1988) conducted a 5-year study with over-17-year-old “Shamouti” orange trees on “Sweet lime” rootstock. Fertigation was evaluated at N application rates of 80, 160, and 280 kg/ha, with no P or K. Fertilization at N rates of 160 and 280 kg/ha, by means of soil application of granular fertilizer (in March) or fertigation (in March-August) was also evaluated. The 5-year average fruit yield was greater by 29% with fertigation than with soil application of granular fertilizer only with N at 160 kg/ha. With N at 280 kg/ha the method of N delivery had no significant effect on the fruit yield (Fig. 7).

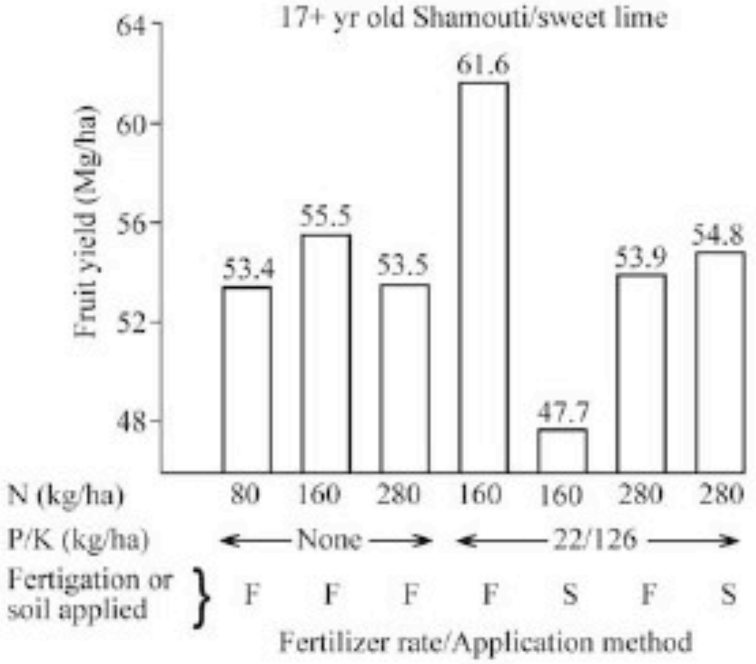

Fig. 7. Five-year mean fruit yields of over-17-year-old “Shamouti” orange trees on “Sweet lime” rootstock, with various rates of N, applied as fertigation (F) without P and K, or at two rates with P and K as a single soil application of granular fertilizer (S) or as fertigation (F) during March through August (extracted from Dasberg et al., 1988).

Fruit quality

Morinaga (2004) conducted studies on “Satsuma” mandarin in southwestern Japan. The premium quality fruit that attract high net returns require the maintenance of sugar and acid contents of 12-14% and about 1%, respectively. To achieve this, Morinaga (2004) developed a new system of drip fertigation combined with year-round plastic mulch. The results presented in Fig. 8 show that under the conventional practice the Brix rating usually was in the range of 9.0-10.9%, whereas under the alternative system of drip fertigation with year-round plastic mulch, the Brix value usually remained within the range of 10-12.9%. The beneficial effects of the latter system included: (i) elimination of the labor cost of annual plastic mulch removal; (ii) improved fruit quality and vigor; (iii) drip fertigation facilitated application of fertilizers underneath the plastic mulch. Morinaga (2004) also concluded that the alternative system improved fruit color, and enhanced the contents of vitamin A, B-carotene, and B-cryptoxanthine; he did not discuss the mechanisms responsible for the enhancement of fruit quality.

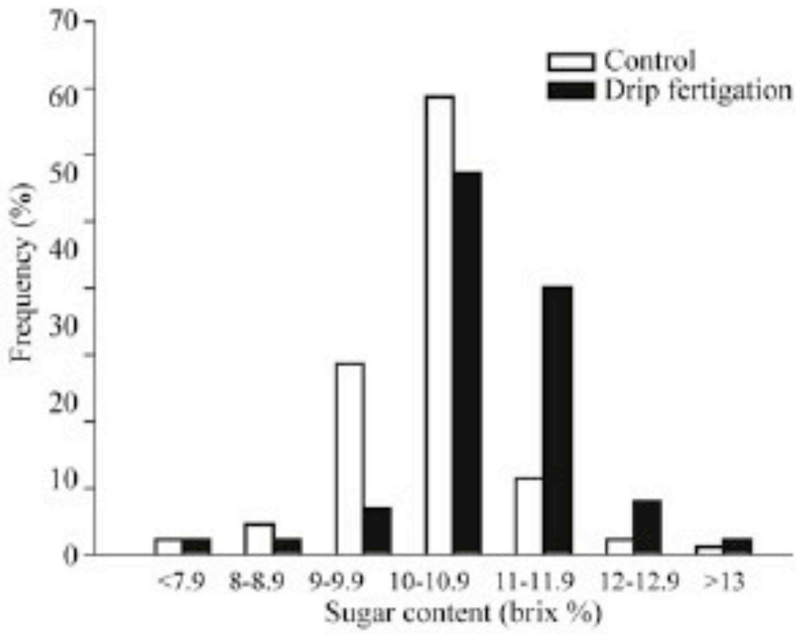

Fig. 8. Comparison of the effects of fertigation vs. broadcast application of dry fertilizer on sugar content of “Satsuma” mandarin (extracted from Morinaga, 2004).

Grapefruit Yield Response

Boman (1996) conducted a 4-year field experiment with mature “Ruby Red” grapefruit trees on “Sour Orange” rootstock planted in St. Lucie County, Florida. Two methods of fertilizer applications were compared, both with N and K applied at approximately 180 and 150 kg/ha, respectively: (i) broadcast application of dry granular sources (annual rates of N and K applied in three equal amounts during Feb./Mar., May/June, and Oct./Nov.); and (ii) one-third of the annual amounts of N and K applied as granular material broadcast in February, with the remainder of the N and K sources applied as fertigation at 2-week intervals during April through early November (i.e. 17-18 fertigations per year). Across the four years, the leaf nutrient concentrations were not significantly influenced by the methods of fertilizer applications. However, as shown in Fig. 9, the yields of fruit (in three out of the four years) and of total soluble solids (in one out of the four years) were significantly greater from the trees that received dry fertilizer broadcast + fertigation treatment than from those that received the full-rate application of N and K as dry broadcast.

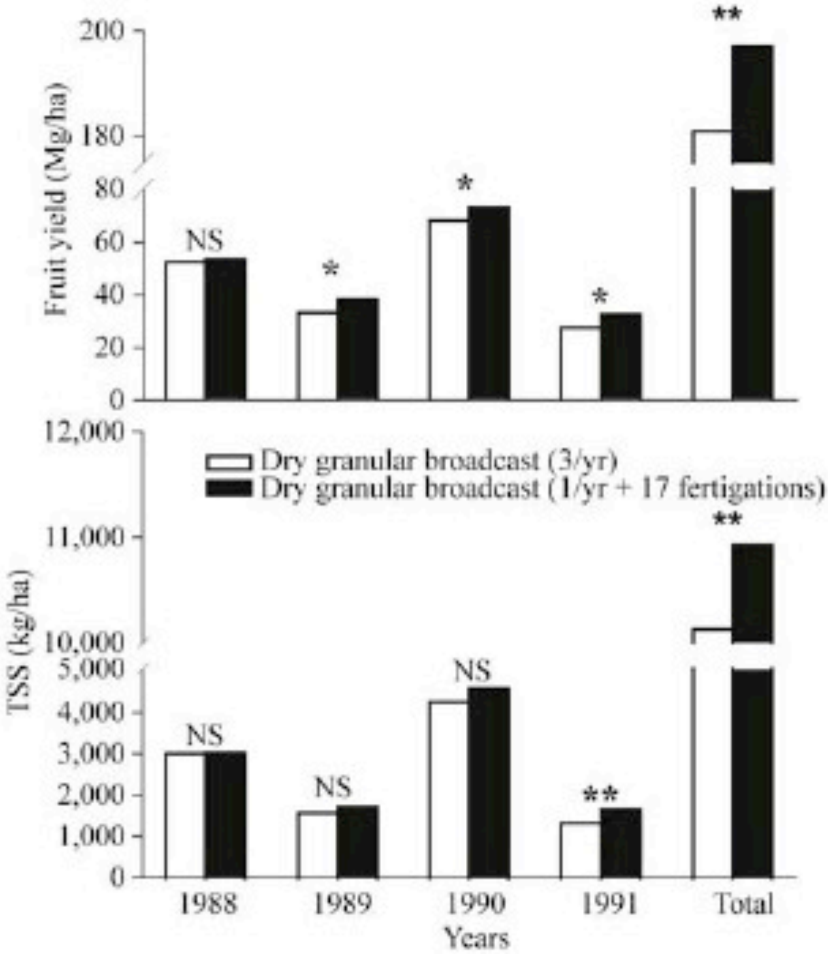

Fig. 9. Fruit yield and soluble solid response of “Ruby Red” grapefruit trees on “Sour orange” rootstock (extracted from Boman, 1996).

A 6-year study by Alva et al. (2005; unpublished data) on over-25-year-old “White Marsh” grapefruit trees on “Sour orange” rootstock, planted at 268 trees/ha, showed that mean fruit yield response (47 to 60 Mg/ha) over the N rate range of 56 to 224 kg/ha was quadratic when fertilization was with dry granular fertilizer broadcast three times per year (Fig. 10). With fertigation, the fruit yield response (47-67 Mg/ha) over the same range of N rates was almost linear. Thus, at the high N rate, the mean fruit yield was 26% greater with fertigation than with dry granular broadcast.

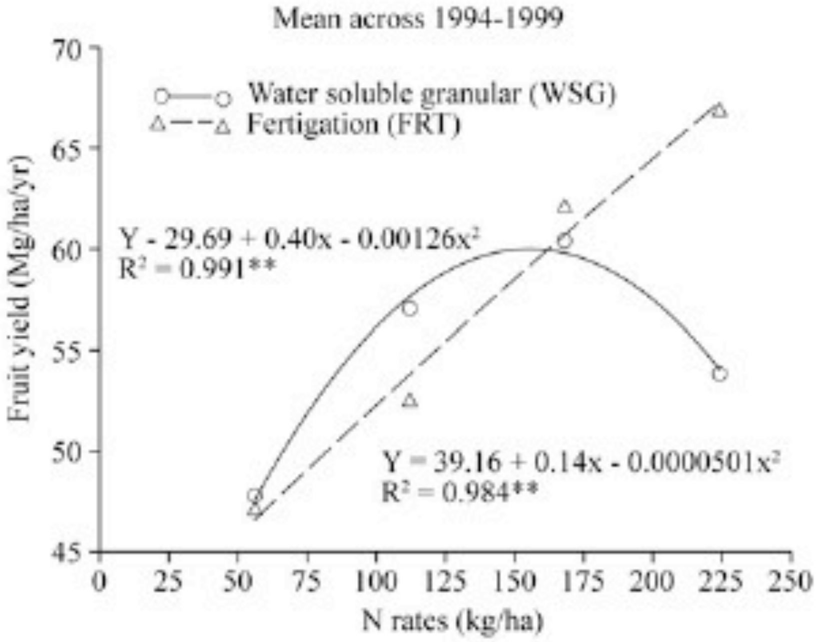

Fig. 10. Fruit yield responses (6-year mean) of over-25-year-old "White Marsh" grapefruit trees on "Sour orange" rootstock to different rates of N, applied as three water-soluble granular broadcast applications per year, or as 15 applications per year via fertigation (Alva et al., 2005, unpublished data).

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Fertigation of Deciduous Fruit Trees: Apple and Sweet Cherry

Denise Neilsen, and Gerry Neilsen

Pacific Agri-Food Research Centre, Summerland, B.C., Canada.
E-mail: neilseng@agr.gc.ca.

Abstract

Nutrient uptake by trees is determined by root interception, soil availability, and tree demand. Fruit trees have low rooting density, especially in the case of dwarfing rootstocks. Mobility in the soil is a key factor in determining nutrient availability, and good management of nutrients requires that supply is matched to demand, in terms of amount, timing and retention in the root-zone, and that nutrients are placed where they can be accessed by roots. Fertigation allows such flexibility in the timing and precision of nutrient supply. The efficiency of N fertigation is closely related to irrigation management. Scheduling irrigation to meet tree evaporative demand minimizes the drainage of excess water through the root zone and the consequent N leaching. Timing the N supply to coincide with the period of rapid canopy development avoids excess N application when tree growth is supported by remobilization of stored N. Fertigation gives greater P and K mobility than broadcasting, increasing the potential for timely application of these nutrients in the root zone. P fertigation is beneficial at planting and as a single application at bloom. Fertigation with K can prevent the development of K-deficiency in drip-irrigated trees on sandy soil. Fertigation with acidic fertilizers through drip systems can be detrimental in coarse-textured soils, where it can result in soil acidification and nutrient deficiencies, which can develop in as short a period as three years.

Keywords: irrigation, nitrogen, phosphorus, potassium, leaching, acidification.

Introduction

In irrigated horticultural production systems, increased precision in the application of both water and nutrients can potentially be achieved by simultaneous application via fertigation (Bar Josef, 1999; Haynes, 1985; Neilsen et al., 1999). This has the advantage of synchronising nutrient supply with plant demand (Millard,1996; Neilsen et al., 2001; Weinbaum et al., 1992), thus enabling reduction in the amount of nutrients applied and reducing environmental impact (Neilsen and Neilsen, 2002; Tagliavini et al., 1997).

Deciduous fruit trees are characterized by a low rooting density, several orders of magnitude lower than that of herbaceous plants (Atkinson, 1980), and apple trees on dwarfing rootstocks have particularly low-density root systems (Neilsen et al., 1997a). Consequently, increased efficiency in nutrient supply requires timely, precise placement and high retention in the main rooting zone.

Plant availability of soil nutrients is determined by a number of factors including inherent fertility, soil chemistry and, in irrigated production systems, by water supply and movement. The behavior of nutrients in irrigated production systems is thus highly affected by their solubility and mobility. For highly mobile nutrients such as N, water management practices can be used to retard movement through the root zone (Neilsen et al., 1998; Neilsen and Neilsen, 2002). Similarly, fertigation and water management can improve the movement of less mobile nutrients such as K into the root zone (Neilsen et al., 2004a; Uriu et al., 1980) and even allow immobile nutrients such as P to be introduced into the root zone (Neilsen et al., 1999).

Fertigation in conjunction with drip irrigation elicits localised plant and soil responses. The placement of nutrients, as modified by water management techniques, may determine root system development, as roots tend to grow in nutrient-rich environments (Jackson et al., 1990). For example, drip irrigation systems concentrated root development in the wetted zone (Bravdo and Proebsting, 1993; Neilsen et al., 2000). The combination of localised nutrient availability and trees with dwarfing rootstocks can result in restricted root systems, which are highly dependent on external nutrient sources (Levin et al., 1979) and thus are susceptible to nutrient and water deficits. Under drip irrigation, the localised application of fertigated NH_4 based fertilizers reduced soil pH (Haynes and Swift, 1986). Fertigation with ammoniacal N and P fertilizers decreased pH (Parchomchuk et al., 1993) and increased cation leaching (Neilsen et al., 1995a) within 3 years of planting in high-density apple orchards. The present paper summarises a series of experiments undertaken in British Columbia, Canada and Washington state, USA which examined the role of fertigation in the sustainable production of deciduous tree fruits.

Nitrogen

The high mobility of N in the soil causes the management of water and N to be inextricably linked. Efficient use of either thus requires both conservative methods of delivery which improve retention in the root zone and also knowledge of the timing and magnitude of N and water demand. The combination of high density production and low pressure, micro-irrigation systems allows controlled inputs of both water and nutrients, potentially to meet demand more precisely than in systems which are rain-fed or use high pressure irrigation. Soil solution nitrate-N concentration rapidly decreased under a single application of N fertilizer with sprinkler irrigation and was likely leached beneath the root zone (Fig. 1a). In contrast, nitrate-N concentration could be maintained at a constant level during fertigation (Fig. 1b) Neilsen et al., 1998).

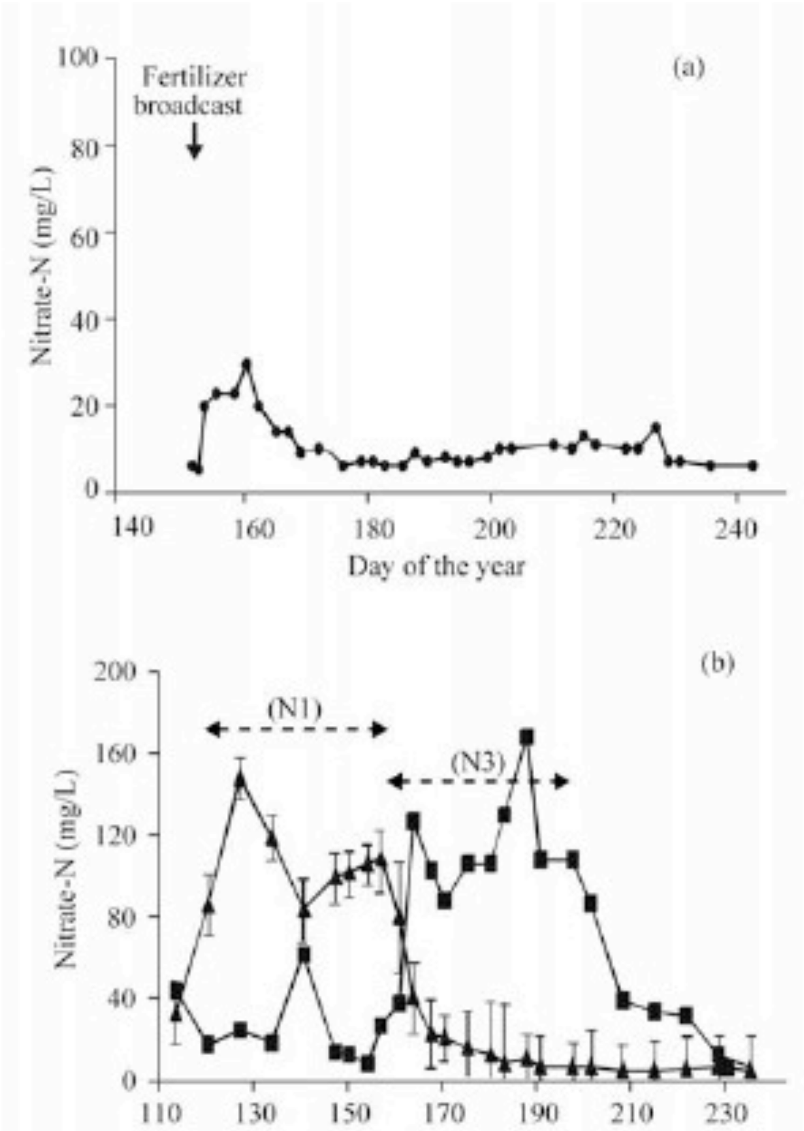

Fig. 1. Soil solution nitrate-N concentration measured throughout the growing season at 30 cm depth in (a) plot receiving a single application of broadcast N fertilizer and weekly sprinkler irrigation and (b) plot receiving daily N fertigation and drip irrigation at different times N1 (▲) and N3 (■).

Water demand is driven by a combination of factors including climate, canopy development and sink requirements for carbon. A range of methods, based on either estimates of evaporative demand imposed by climate (Allen et al., 1998) or soil moisture depletion have been used to determine irrigation water requirements. In the experiments described herein, unless otherwise stated, irrigation was automatically applied each day, based on evaporation, as measured by an electronic atmometer (ETGage Co., Loveland, Co), and modified according to a crop-coefficient curve, based on canopy development. Weekly soil moisture measurements via Time Domain Reflectrometry (TDR) (Topp and Davis, 1985) were used to verify application rates. The amount of water saved by scheduling irrigation to meet demand can be quite large. In an extreme case, where water was applied throughout the season at a constant rate, sufficient to meet peak demand, applications per tree were twice (1,304 L/yr) the amount applied under scheduled irrigation (646 L/yr) (Neilsen and Neilsen, 2002). Losses of water (Fig. 2a) and N (Fig. 2b) beneath the root zone, as measured with a passive, capillary-wick sampling system (Neilsen and Neilsen, 2002) were significantly lower for scheduled than for constant-rate irrigation in the spring and fall, i.e. when evaporative demand was lower than the mid-summer maximum.

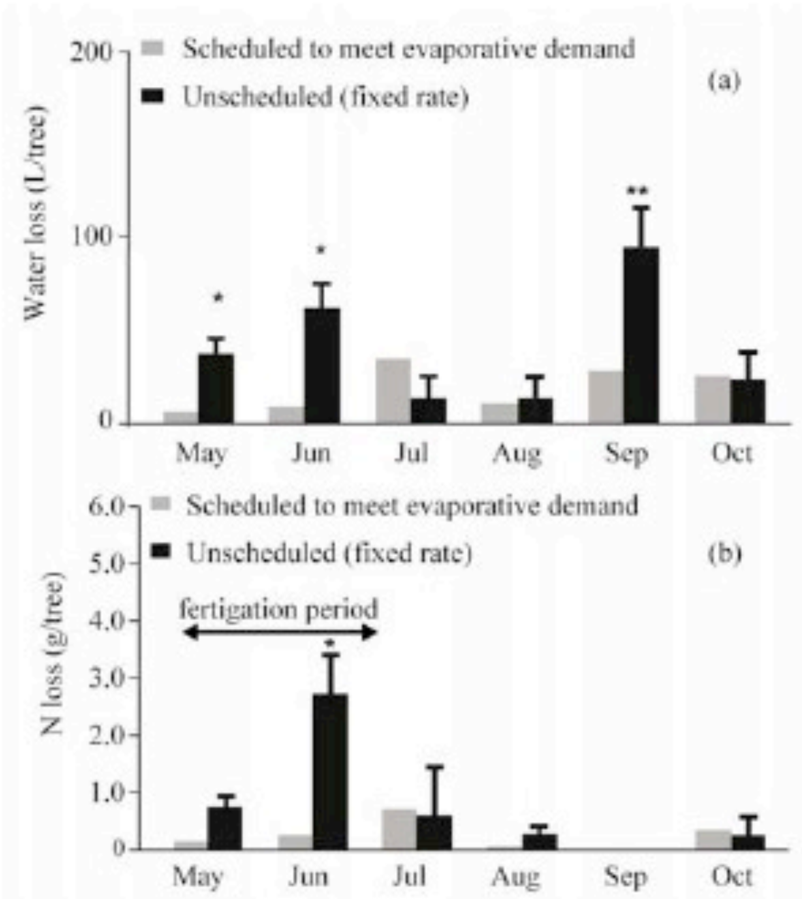

Fig. 2. Water drainage (a) and N flux (b) beneath the root zone in response to drip irrigation applied at either maximum rate or scheduled to meet evaporative demand using an atmometer either maximum rate or scheduled to meet evaporative demand using an atmometer.

In sandy soils, it is also possible to over-apply water when drip irrigation is scheduled to meet evaporative demand. The amount of water applied per tree through micro-sprinklers (20 L/hr) was 31% greater than that applied through drippers (8 L/hr) in a young Braeburn/M.26 planting in British Columbia. Losses of water and N beneath the root zone, as measured in passive capillary-wick samplers, were 12 and 7% of total additions for drippers and micro-sprinklers, respectively (Fig. 3a and 3b). Losses from drip irrigation were higher than for micro-sprinkler during mid-summer, probably because volumes of water, supplied on a twice daily basis to meet evaporative demand measured with an atmometer, exceeded the moisture-holding capacity of the loamy sand soil. An examination of the spatial distribution of water losses indicated that the majority was lost directly beneath the drip emitter.

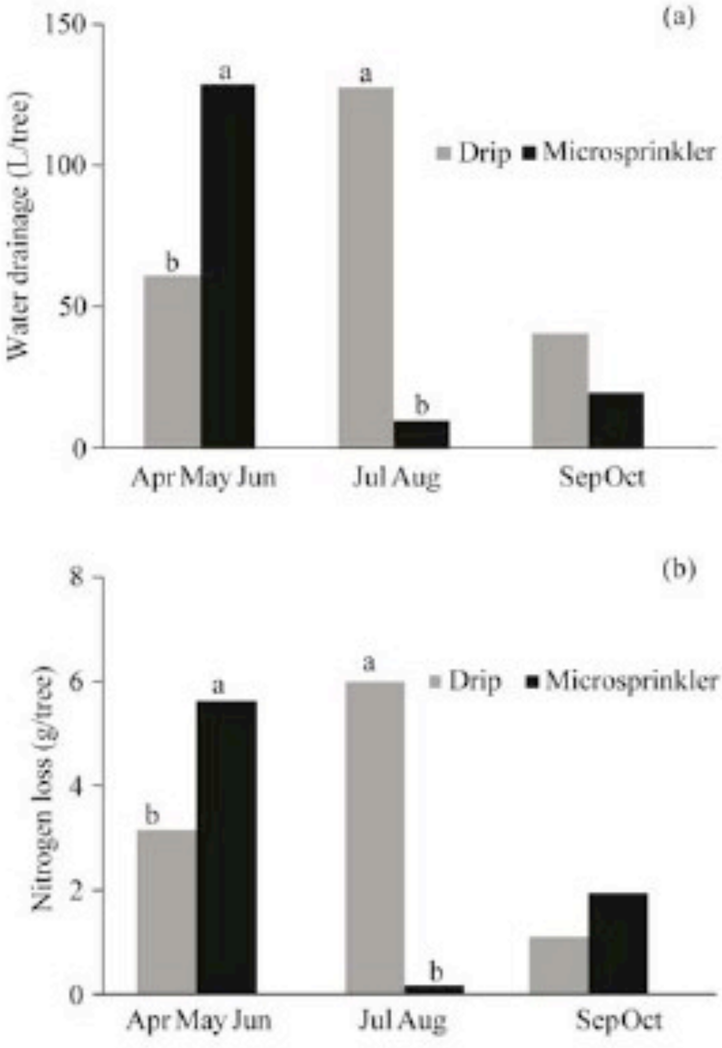

Fig. 3. Water drainage (a) and N flux (b) beneath the root zone in response to drip or micro sprinkler irrigation.

It has been well established that woody perennials withdraw N from foliage in the fall and that N is remobilised from storage in the spring, to support new growth (Millard, 1996; Tagliavini et al., 1997, 1998). For apple trees, remobilisation is the major source of N for development of the spur leaf canopy (Neilsen et al., 1997a, 2001), whereas the shoot leaf canopy derives N from both remobilisation and uptake, and large-scale root uptake commences around bloom (Guak et al., 2003). Thus, application of fertilizer N should be timed to match maximum demand, which occurs during shoot leaf canopy development, that is, during the 6 weeks after bloom.

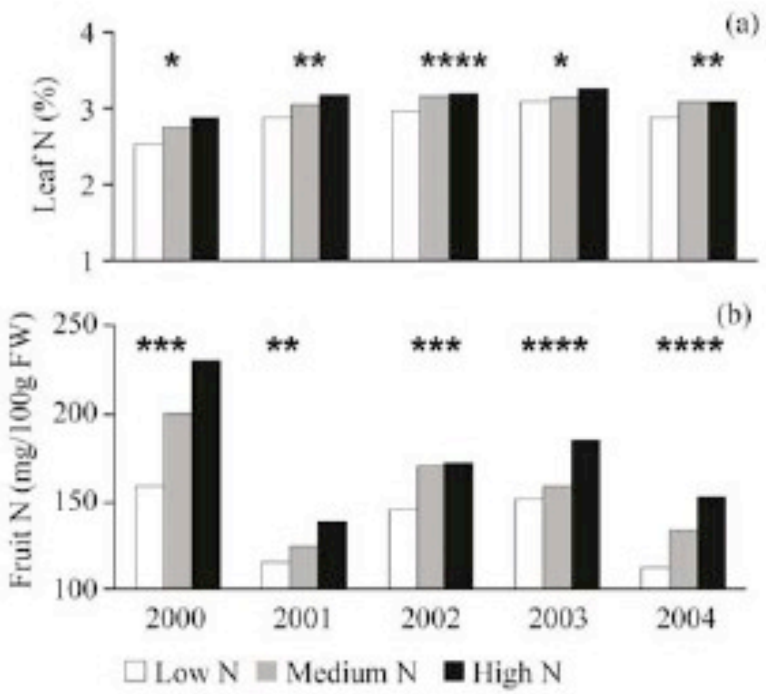

Fig. 4. Leaf (a) and fruit (b) N concentration over five years in Lapins/Gisela 5 sweet cherry trees in response to three levels of fertigated N (low) 42 mg/L (medium) 84 mg/L (high) 168 mg/L.

Nitrogen requirements for sweet cherry are less well understood, and most soils cannot supply sufficient N for sweet cherry orchards. Recommended leaf N concentrations range from 2.4-3.4% and high input levels of N (50-150 kg/ha) may be recommended, particularly on coarse-textured soils (Hanson and Proebsting, 1996). In a recent 5-year study, fertigated N applied at 42, 84 or 168 ppm for 8 weeks after bloom was compared with broadcast N (75 kg/ha) in a planting of Lapins/Gisela 5 sweet cherry (Neilsen et al., 2004a). Although leaf and fruit N concentration increased linearly with fertigated N rate (Fig. 4), fruit yield was either unaffected or negatively related to N application rate (Fig. 5) as also was fruit size (data not shown). On average, the low-N fertigation treatment supplied N at about 63 kg/ha, indicating that a lower rate of N, applied daily for eight weeks post-bloom was apparently more effective than a single, broadcast application.

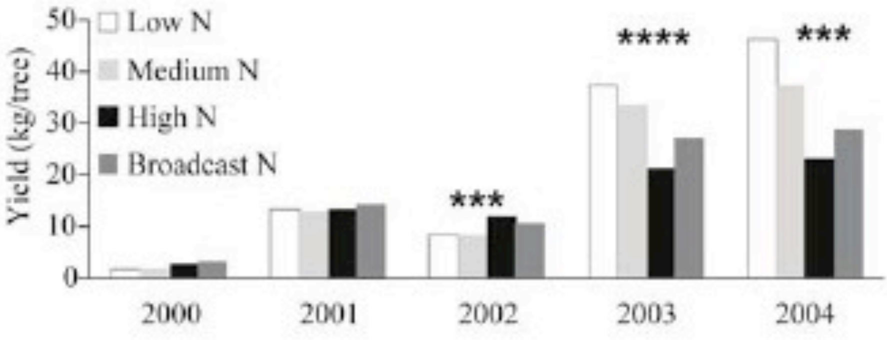

Fig. 5. Yield over five years in Lapins/Gisela 5 sweet cherry trees in response to three levels of fertigated N – (low) 42 mg/L (medium) 84 mg/L, and (high) 168 mg/L – and broadcast N (75 kg/ha).

Potassium

Fertigation with acidifying fertilizers can lead to the depletion of K and other soluble bases to a depth of 30 cm beneath the drip emitter after only 3 years of application (Parchomchuk et al., 1993). The susceptibility to K deficiency under drip irrigation has been attributed to the high proportion of roots that are located in the zone of soil K depletion. To improve orchard nutrition, potassium can be effectively applied via fertigation. Daily K fertigation from mid-June to mid-August at a per-tree rate of 15 g/yr maintained a higher K concentration in the soil solution (Fig. 6), and, in response, leaf K concentrations were maintained above deficiency levels, fruit K and Mg concentrations increased, and fruit yield, size, titratable acidity and red color at harvest all increased in the apple cultivars “Gala”, “Fuji”, “Fiesta” and “Spartan” (Neilsen et al., 2004b). The form of K fertilizer appeared to have little effect on tree response, as demonstrated in a 3-year experiment with “Jonagold” on M.9 rootstock in which K in various forms was fertigated daily over a 6-week period from late June to mid-August (Table 1). There were no major differences in leaf and fruit K concentration among the K-form treatments, nor was there any effect of the K treatments on bitter-pit incidence, which was generally high.

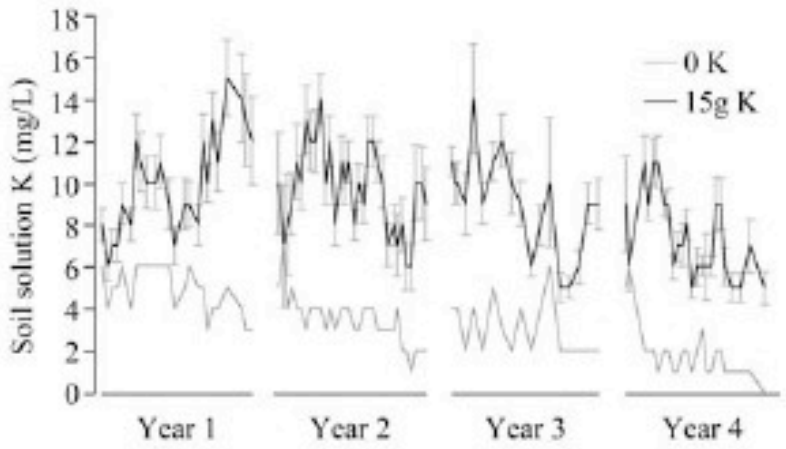

Fig. 6. Soil solution K concentration at 30 cm beneath drip emitters in response to K applications of 0 and 15 g/yr per tree.

Table 1. Effect of K-fertilizer form on K-nutrition and bitter-pit expression for >Jonagold= on M.9 rootstock grown on sandy loam soil, 2000-2002.

Fertigation treatment[y]	Mid-July leaf K concentration			Harvest fruit K concentration			Harvest bitter-pit incidence		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
	-------- % DW ---------			mg K/100 g FW			---------- % ----------		
Control (no K)	1.38c	1.58c	1.46c	106	105b	101b	8	15	17
KCI (15 g K/tree)	1.60b	1.81b	1.73b	110	124a	115a	2	13	18
KCI (30 g K/tree)	1.67ab	1.96b	1.83ab	112	124a	123a	5	5	18
KMag (15 g K/tree)	1.66ab	1.89ab	1.74b	112	124a	116a	8	10	27
KMag (30 g K/tree)	1.72a	1.98a	1.85ab	119	129a	123a	7	8	20
K_2SO_4 (30 g K/tree)	1.66ab	2.00a	1.91a	116	118a	123a	2	5	10
K thiosulfate (30 g K/tree)	1.76a	2.01a	1.94a	112	124a	122a	8	4	13
	****	****	****	NS	*	****	NS	NS	NS

Phosphorus

Fertigation is known to increase P mobility in sandy soils (O'Neil et al.,1979). The improved mobility has been attributed to the movement of P by mass flow with irrigation waters after saturation of sorption sites near the point of application. Therefore, fertigation has the potential for improving the amount of P available at root surfaces, particularly in coarse-textured soils, which have low P sorption capacity. Application of 17.5 g of P per tree in an orchard, as a single dose of ammonium polyphosphate, immediately resulted in elevated extractable P at 30 cm depth (the major rooting depth for this soil) directly beneath the drip emitter (Neilsen et al., 1997b). One benefit of improved P nutrition for 1-year-old apple trees have was increased flowering in the second year (Neilsen et al., 1990). Fertigation of the same amount of P via 8 weekly applications immediately after planting rather than as a single annual application at planting time was more effective at increasing leaf P and tree vigour in first year for "Mcintosh" and "Jonagold" apple on M.26 rootstock (Neilsen et al.,1993). Fertigation with 20 g of P per tree as ammonium polyphosphate, in a single annual application, in conjunction with adequate fertigated N in the 4 weeks immediately post bloom improved fruit yield and quality in a multi-variety apple trial: cumulative yield in years 2 through 6 was higher in the NP- than in the N-treatment for all five apple cultivars ("Ambrosia", "Cameo", "Fuji", "Gala", and "Silken") grown on M.9 rootstock (Table 2). The P-treated fruit also frequently displayed greater membrane stability and resistance to browning when cut (data not shown).

Table 2. Effect of fertigation treatment on yield of five apple cultivars (>Ambrosia=, >Cameo=,>Fuji=,>Gala= and >Silken=) on M.9 rootstock on Skaha sandy loam soil.

Fertigation treatment	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Cumulative
	---------------------------- Yield (kg/tree) ----------------------------					
1. N (168 mg N/L, 0-4 weeks post full bloom)	1.9	7.7	10.4	13.5	5.7	39.8
2. N (as above) + P pulsed (20 g P/tree as 10-34-0 1 week post full bloom)	2.0	10.3	13.2	15.3	7.7	47.8
Significane	NS	****	*	NS	**	*

Effects of fertigation on soil properties

Fertigating ammoniacal forms of N and P can affect the base status of soils, because transformation of ammonium to nitrate is an acidifying process that may also accelerate leaching. Fertigation with various combinations of N and P as soluble ammonium nitrate and ammonium polyphosphate decreased extractable soil K in the topmost 30 cm of a sandy loam directly beneath the drip emitter, and redistributed K to the edges of the wetted zone (Parchomchuk et al.,1993).

The widespread nature of this problem was indicated in a survey of 20 commercial orchards which had undergone 3 to 5 years of NP-fertigation (Neilsen et al.,1995a). Soil pH, extractable soil bases and soil B, as measured in the 0-15 cm layer directly beneath the drip emitter, were all reduced (Table 3). In light of this survey, a soil test was designed to determine the susceptibility of soils to acidification (Neilsen et al., 1995b). The acidification resistance index (ARI) was developed from analysis of buffer curves for 50 soils of diverse composition; it was defined as the amount of acid required to reduce soil pH from initial status to pH 5.0. These values were then compared with common soil test analysis data and a relationship was defined between the acidification resistance index, the soil pH, and soil extractable bases. It was recommended that soils with a low acidification resistance index be fertigated with NO_3-based rather than NH_4–based fertilizers.

Table 3. Soil chemical changes at 30 cm depth directly beneath the emitter, in 20 orchards (3-5 years old) receiving drip irrigation and fertigation with NH_4–based fertilizers.

	[z]pH	Ca	Mg	K	B
		-------------------- ppm	--------------------		
Between rows	7.0	1,235	144	211	0.97
Beneath emitter	6.2	911	114	88	0.19
Significance	***	**	**	**	****

[z] pH (1:2 soil:water); Ca, Mg, K extracted in 0.25M acetic acid + 0.015M NH_4F (van Lierop and Gough, 1989); B (hot water extractable).
*,**,***,**** significantly different at $p<0.05$, 0.01, 0.001, 0.0001

Conclusions

Fertigation offers the potential to overcome the low fertility of soils by timely delivery of key nutrients to the main rooting zone in orchards. Efficient use of N, however, depends upon reducing excessive drainage of water and improving our understanding of the dynamics of tree N uptake. In irrigated systems this means development of conservative scheduling methods to avoid excessive water application. Understanding the important role of N-remobilization in the growth cycle of apple trees can lead to reduced application of N fertilizers when tree needs are met by internal N-cycling. In contrast, delivery of more immobile nutrients such as P and K directly to the roots is facilitated when these nutrients are supplied in solution. For example, a single annual pulse application of 20 g of P per tree around bloom time has improved apple yield and fruit quality. Application of K in the form of any readily soluble K-fertilizer can increase tree K uptake and so prevent the development of K-deficiency in drip-irrigated trees grown on coarse-textured soils.

However, fertigation has the potential to accelerate soil degradation. In particular, the use of ammoniacal fertilizers and excessive applications of water may cause a reduction in pH in unbuffered soils, and loss of bases and soluble nutrients such as N and B. This is most evident in the soil immediately beneath the emitters of drip irrigation systems.

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Manipulating Grapevine Annual Shoot Growth, Yield and Composition of Grapes Using Fertigation

Michael Treeby

CSIRO Plant Industry, Horticulture Unit, River Avenue, Merbein, Victoria, Australia. E-mail: michael.treeby@csiro.au.

Abstract

Grape producers are increasingly using pressurized water delivery systems to deliver soluble nutrient salts to vine roots. Coupled with tight water management, such systems allow control over the amount supplied and the timing of that supply, and hence greater control over shoot growth, leaf function and grape yield and composition. There are many permutations and combinations of timing of supply and amounts delivered, which, when coupled with the many environments, soil types, varieties and rootstocks used and grape end uses, makes the notion of a single universal program untenable. The timing of nutrient uptake by grapevines, which can be estimated using published data, and the amounts removed can be the basis of a fertigation program. The modifications required may need to address the specific needs of the variety being grown, the rootstock used and grape end use, and be site specific. Even with fine tuning, however, season-to-season variation in crop size is difficult to accommodate, raising the possibility that decision support frameworks that incorporate perenniality and encapsulate vine growth and development functions, yield potential determination and intra-vine nutrient dynamics may represent the next advance in the use of fertigation as a management tool in grape production.

Keywords: minerals, grapevines, grape composition.

Introduction

Grapes and grape products are an important part of many cultures around the world. World grape production is for the most part based on selections of Vitis vinifera L. Grapes are consumed fresh and dried, and crushed grapes are consumed as juice or as still, sparkling or fortified wines following vinification. Worldwide, ca. 60.9 million tonnes of grapes were harvested from 7.5 million hectares in 2003 (Anon., 2004). Generally, approximately 45% of the grapes produced worldwide are used for producing fermented beverages, 22% are consumed as table grapes, 16% are dried and the remainder consumed as grape juice.

For many of these end uses, grape berry appearance and composition are important drivers of production technology, and for other end uses yield remains the primary driver. Tools that confer some degree of control over shoot growth, leaf physiology and reproductive growth and development are an important part of meeting consumer demands profitably. Clearly, water and mineral nutrients are critical inputs in this regard, and the interaction between the two is recognized (e.g. Ussahatanonta et al., 1996), although some trial designs have not differentiated between the effect of water volume applied from the effect of fertilizer rate (Almela et al., 1999; Klein et al., 2000). When one factor is held constant, variation in the other usually results in significant responses.

Fertigation can be defined as the delivery of essential mineral nutrients as dissolved salts to the roots of plants in water primarily supplied to meet plant water needs. The concept's primary objective was ease of management, and efficiency and crop manipulation considerations were later spinoffs. There is a prima facie case that the interception and efficiency of uptake of nutrients supplied via a fertigation system should be higher compared to surface application. This would be particularly so if the duration and timing of irrigation events avoid waterlogging and leaching on the one hand and water stress on the other. But, it must be recognized that there has been no direct side-by-side comparison of the interception and uptake efficiency of dissolved nutrients delivered to the rootzone via irrigation water in pressurized systems compared to nutrients broadcast as dry fertilizers on to the soil surface. Nutrient use efficiency (i.e. mt output/kg input) is probably of lesser importance compared to the potential benefits to be derived from being able to better control shoot growth and grape composition.

Potentially, a bewildering number of permutations and combinations of timing, nutrient salts and amounts are possible using fertigation techniques. Equally daunting is the range of vinifera genotypes used as direct producers or scions on a range of Vitis species and interspecific Vitis hybrid rootstocks (see Ambrosi et al., 1994). Rootstock effects on scion mineral nutrient status and differences in the mineral nutrient status of different vinifera genotypes grown under the same conditions have been known for many years (e.g. Cook and Lider, 1964). Coupled with multiple end uses, varying specifications within general end use classes and widely differing soil and environmental conditions between grape growing regions, the notion that a universal fertigation program will meet all needs is unrealistic. Recognition of these complexities is reflected in industry publications - general principles are discussed, but definitive programs are not detailed (Conradie and van Zyl, 1989; Treeby et al., 2004).

This article uses published data to illustrate some of the factors that may be important in designing aspects of a fertigation program to achieve particular grape yield and composition outcomes. Deficiencies in knowledge that limit realization of the potential benefits that can be obtained by grape producers from exerting control over mineral nutrient supply are highlighted. The discussion is principally confined to the macro-nutrients N, P and K because these mineral nutrients are the nutrients removed from vineyards in the largest amounts. Futhermore, their supply is relatively easily manipulated and, on the basis of the amount of data published, have the greatest impact on shoot growth, leaf function, reproductive development and grape composition in most situations where grapes are produced. Nonetheless, mineral nutrients other N, P and K are supplied in fertigation programs, for example Mg (Gurovich et al., 1994) and B (Peacock, 2004). The hardware needed to deliver dissolved nutrients in irrigation water, and the nutrient sources available, are well covered by Burt et al. (1995).

Timing of nutrient uptake and nutrient dynamics within grapevines

Critical to the successful use of fertigation is an appreciation of the timing of nutrient absorption by vine roots during the growing season and the impact of nutrients taken up during particular periods on the performance parameters of interest. Approximate proportions of the total seasonal uptake that can be attributed to uptake during distinct phenological stages can be estimated using data collected from potted vines (Conradie 1980, 1981), intensive destructive sampling programs conducted on established vines in the field (Alexander 1957; Lafon et al., 1965; Löhnertz, 1988; Schaller et al., 1989; Wermelinger and Koblet, 1990; Williams and Biscay, 1991) and the impact of supply at particular stages (Peacock et al., 1989; Conradie, 1990, 1991, 1992; Christensen et al., 1994; Glad et al., 1994). Using data from the aforementioned studies and data collected from local trials, estimates of the total uptake of N, P and K in a season by grapevines growing in a warm irrigated region of south eastern Australia are presented in Table 1. One would expect the proportions to change according to the growing environment: for example, the importance of uptake during the postharvest period would diminish if the length of time between grape harvest and leaf fall is short and increase if that length of time is greater.

Table 1. Estimates of approximate proportions of total seasonal N, P and K uptake attributable to uptake during particular growth stages for grapevines growing in a warm irrigated region of south east Australia. Estimates based on published data (see text) and regional data (Treeby and Wheatley – unpublished).

Nutrient	Growth stage				
	Budburst - bloom	Bloom - set	Set - veraison	Veraison - harvest	Harvest - leaf fall
	------------- Total season's uptake in each stage (%) -------------				
N	10	15	35	10	30
P	25	40	25	0	10
K	20	30	25	10	15

The estimates presented in Table 1 probably represent uptake behaviour if nutrient supply is non-limiting. Because the concentrations of these nutrients in the shoots over the course of the growing season will, to a greater or lesser extent, affect leaf function, annual biomass production, bud fertility and grape composition, uptake of these nutrients during these stages needs to be manipulated.

Amounts supplied and removed

The amounts of N, P and K removed may serve as an indication of the minimum amount needed to at least maintain soil fertility. In a warm irrigated grape growing region of south east Australia, N, P and K removals amounted to 18 and 43, 3 and 7 and 26 and 63 kg/ha in Sultanas used for producing dried vine fruit and in Cabernet sauvignon grapes used for wine, respectively (Table 2). For Sultana, the amounts removed per hectare were strongly correlated with yield ($r^2 > 0.9$), but the amounts of N, P and K per unit output were not as well correlated with yield ($r^2 = 0.62$, 0.44 and 0.41 for N, P and K, respectively). This could indicate that factors other than sink size affect transport of mineral nutrients to the berries. There is ample evidence that the amounts of N and K in grapes at harvest can be manipulated by supply (e.g. Spayd et al., 1994; Ruhl, 1989). The higher removals in Cabernet compared to Sultana may be related to the presence of seeds: approximately 50, 40 and 85% of the total amounts of N, P and K, respectively, in Cabernet berries are present in the seeds, while Sultana is seedless. Removals data are useful as a starting point to estimate needs, but may not relate to the levels required for particular grape end use, and do not give any indication as to what level of inputs are required to maintain canopy function while the berries are maturing and during the period from harvest to leaf fall.

Table 2. Yields and N, P and K removals from a Sultana vineyard and a Cabernet sauvignon vineyard in a warm irrigated region of south eastern Australia.

Variety	Mean yield	N	P	K
		---------------	kg/ha	----------------
Sultana	4 (dried vine fruit mt/ha)	18	3	26
Cabernet sauvignon	22 (mt/ha)	43	7	63

Levels of nutrient inputs published in more recent years have tended to be more moderate, and more closely match estimates of removals (Table 3). The absence of rigorous comparative data may be a factor in the relatively high inputs used early in the development of fertigation as a means of supplying grapevine nutrient needs, as well as possibly reflecting the site-specific soil conditions used for those.

Nitrogen

Possibly because nitrogen supply frequently limits shoot growth and grape yield, there have been many studies conducted on the impact of various rates and timing of supply. When water is not limiting grapevines respond to increasing N supply by taking up more N, increasing annual biomass production (Kliewer, 1971; Alleweldt et al., 1984; Zerihun and Treeby, 2002), and floral bud initiation and hence final yield may be greater in comparison to vines not supplied N (Spayd et al., 1993). Nitrogen supply also affects the amount of N in berries: too much N results in too rapid fermentation and undesirable compounds potentially forming in the final wine, while too little results in stalled fermentations and H_2S production (Henschke and Jiranek, 1993). In addition, too much N can result in less anthocyanin in red grapes (Kliewer, 1977; Hilbert et al., 2003). Balancing producers' needs for profitable levels of productivity and wine makers' needs for grapes of a suitable composition and trouble free vinification remains a challenge. The limited data available suggests that, generally, N applied in autumn the previous season or during summer of the current season will result in more berry N at harvest, but that the response is affected by rootstock (Treeby et al., 2000). The implication of this is that a fertigation program to supply sufficient N to ensure trouble free vinification may need to be rootstock dependent. A considerable gap in our knowledge exists regarding the ways in which rootstock genotypes affect scion N status and intra-vine N dynamics.

Phosphorus

There is much less understanding of the impact of varying amounts and availability of P to vine roots during the growing season on shoot growth and grape yield and composition at harvest. Chronic P deficiency is known in California (Skinner et al., 1988) and Western Australia (Robinson, 1992), and poor supply of P can negatively affect vine productivity and wine quality (Bravdo and Hepner, 1987). Relative to N and K, P removals are low, and the chemistry of phosphate availability across the normal range of soil pH mean that it is difficult to supply too much P. Nonetheless, P-induced Zn deficiency has been observed in Germany, but is very dependent on rootstock (Marschner and Schrobb, 1977). A further complication encountered supplying dissolved phosphate salts is the formation of sparingly soluble calcium phosphates in hard water (Burt et al., 1995).

Potassium

Potassium is needed in large amounts by grapevines, and significant amounts are removed from vineyards in the grapes at harvest. However, too much K in red wine grapes can be associated with wines of poor hue and low colour stability due to more malate relative to tartrate (Hale, 1977). Much of the potassium present in grape berries at harvest is translocated from the leaves to the berries concurrently with the transport of sucrose to the berries during the maturation process. Large amounts of K are frequently applied during this period to hasten grape maturation, particularly for table grape production. However, there is little evidence that sugar accumulation by berries is enhanced by large doses of K, but K accumulation by berries can be enhanced by K supply (e.g. Conradie and de Wet, 1985; Bravdo and Hepner, 1987).

Monitoring tools

Sampling and analysis of specific tissues at specific times remains the primary source of information to assess the efficacy of any fertilizer program. Debate continues on the most appropriate tissue to sample and the most appropriate time to sample. In some parts of the world, the petiole of the leaf opposite the basal bunch at 50% cap fall is used (Robinson and McCarthy, 1985), and in other parts, the leaf blade (Conradie, 1985). The analytical data are then compared to standards that are essentially a synthesis of experimental data and population statistics (e.g. Robinson et al., 1997) and reflect the relationship between vine nutrient status and vine performance, usually yield. The development of interpretative nutrient standards in relation to other aspects of vine performance (e.g. grape composition at harvest), for other clearly discernible phenological milestones (e.g. veraison) would be of great use in assessing the efficacy of any fertigation program. Technically, the rapid measurement of NO_3^--N and K^+ in the expressed sap of grapevine leaf blades or petioles is relatively simple (Nagarajah, 1999), making it feasible to conduct measurements throughout the growing season. However, in the case of NO_3^--N, for reasons not well understood, levels are affected by which petioles are sampled and levels vary significantly within and between seasons (Christensen, 1969; Spayd et al., 1993), making such measurements of limited use until a body of data is accumulated that allows the development of an interpretative framework. More structured approaches to removing the confounding effects of growth dilution on apparent mineral nutrient concentrations at flowering have been developed (Anon., 2005), and incorporation of this approach should be considered when developing interpretative frameworks including mineral nutrient data.

Decision support systems

Decision support systems are being used increasingly in modern agriculture systems, particularly in those systems exploiting annual plants. Such systems can be empirical, and relatively simple, or more complex multi-dimensional frameworks incorporating mechanistic models reflecting a deeper understanding of the underlying physiology (Le Bot et al., 1998). The strength of mechanistic models lie in their ability - beyond the data set used for parametization - to predict the outcomes of various scenarios in a number of environments. As knowledge grows of the physiology underpinning temporal patterns of uptake, storage, re-mobilization and partitioning of mineral nutrients within grapevines, so too will the efficacy of models built on that understanding have in terms of predicting grapevine nutrient needs in relation to desired canopy behaviour and grape composition at harvest. The season-to-season variability in crop size (and hence the size of the sink to be manipulated) and the storage of carbohydrates and mineral nutrients in, and mobilization from, the perennial structures necessitates the incorporation of perenniality in any model that will be the basis of an advanced decision support framework in perennial horticulture.

The table grape fertigation decision support framework developed by Gurovich et al. (1994) (Fig. 1) incorporates models based on a simple mechanistic understanding of vine nutrient balance, and importantly, recognizes the differences between scion genotypes and modifies according to yield and petiole data from season to season. Soil water depletion is a key data input in the framework, but perenniality is not a structural feature.

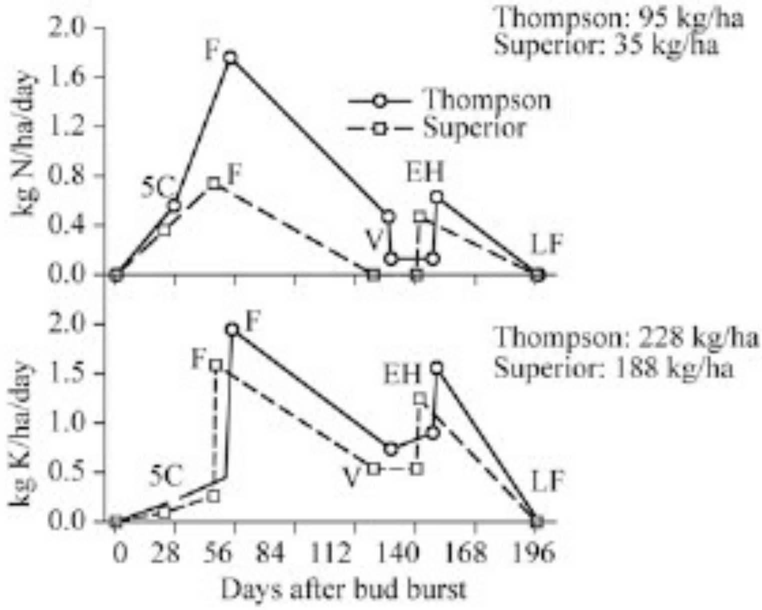

Fig. 1. Basic N and K fertigation program for 2 table grape varieties. 5C = average of 5 clusters visible on vine; F = flowering; V = veraison; EH = end of harvest; LF = leaf fall. Adapted from Gurovich et al. (1994) and reprinted by permission of the American Society for Enology and Viticulture -Proceedings of the International Symposium on Table Grape Production (1994).

Wermelinger et al. (1991) published details of a C and N partitioning model that partly addresses the perenniality issue by using a measure of N reserves at budburst as a starting input. This type of approach may allow producers to predict the effect of N supply scenarios for the current season on potential N reserves and demand for reserve and fertilizer N during the following season, and would be a significant advance. As indicated above, the development of suitable measurement tools and standards against which performance can be assessed will be integral to using the predictive power of such models.

Table 3. Published total seasonal inputs for N, P and K delivered via fertigation.

Location	Variety	Rootstock	End use	kg/ha/season N	kg/ha/season P	kg/ha/season K	Source
Israel	Cabernet sauvignon	Richter 110	wine	40-250	65	0-470	Bravdo and Hepner (1980)
Israel	Cabernet sauvignon	Richter 110	wine	50-280	0-90	0-430	Bravdo et al. (1983)
Israel	Cabernet sauvignon	Richter 110	wine	44-358	60	0-520	Bravdo and Hepner (1987)
USA	White Riesling	Own roots	wine	0-224	-	-	Spayd et al. (1993)
Chile	Thompson Seedless Flame Seedless Superior Christmas Rose Redglobe	(not stated)	table	100-135 47-100 30-65 50-100 55-100	11-14 5-10 4-6 5-10 6-10	72-128 60-128 38-83 64-128 70-128	Gurovich et al. (1994)
Spain	Monastrell	Richter 110	wine	60-80	6-17	36-110	Almela et al. (1999)
Israel	Sauvignon blanc Merlot Cabernet sauvignon	(not stated)	wine	49-81 71-119 53-88	6-9 8-14 6-10	-	Klein et al. (2000)
Australia	Shiraz	Teleki 5 C Ramsey Schwarzmann Own roots	wine	0-40	-	-	Treeby et al. (2000)
Australia	Shiraz		wine	40	-	-	Wade et al. (2004)

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Non-Nutritional Fertigation Effects as a Challenge for Improved Production and Quality in Horticulture

[1] Volker Römheld, [2]S. Jiménez-Becker, [1]Günter Neumann, [1]Joseph Patrick Gweyi-Onyango, [3]L. Puelschen, [4]Wolfram Spreer, and [5]Fritz Bangerth

[1] Institute of Plant Nutrition (330), University of Hohenheim, 70593 Stuttgart, Germany
[2]Vegetable Production, University of Almería, Carretera Sacramento s/n., 04120 Almería, Spain
[3]Kemira –Espoo Research Centre, Luoteisrinne 2, FIN-02271 Espoo, Finland
[4]Process Engineering in Plant Production, University of Hohenheim, 70593 Stuttgart, Germany
[5]Institute for Special Crop Cultivation and Crop Physiology (370), University of Hohenheim, 70593 Stuttgart, Germany

Corresponding author: Volker Römheld, Institute of Plant Nutrition (330), University of Hohenheim, 70593 Stuttgart, Germany. E-mail: roemheld@uni-hohenheim.de.

Abstract

Fertigation is generally accepted as a technology to improve use efficiency of often limited irrigation water and fertilizers, mainly in horticultural production. However, the possibility to use fertigation as a strategy to exploit the physiological and genetic potential of horticultural crops, independently of purely nutritional effects, has not attracted much attention. Three case studies are presented and discussed to demonstrate that this strategy could present a promising challenge for the near future. The use of an acidifying N/P fertilizer (urea phosphate) in fertigation systems is presented as a means to achieve earlier productivity (plant earliness) in vegetable production systems on calcareous soils. In a second case study, prospects for application of different nitrogen forms to manipulate formation of lateral shoots in tomato and cereals are discussed. A third case study addressed the possible induction of off-season lychee flowering by partial root drying or by a micro-nutrient (B, Zn) deficiency treatment, applied via fertigation. In all three examples, changes in phytohormonal balances, induced by fertigation treatments played a decisive role in regulating plant development for earlier and better yield. Thus, improved knowledge of hormonal regulation of plant growth and development, and

integration of this knowledge into fertigation systems could be a promising strategy to improve fertigation technologies in horticultural production.

Keywords: cucumber, fertigation, lychee, morphogenesis, plant earliness, phytohormones, off-season flowering, tomato.

Introduction

Fertigation is a technology, increasingly employed in horticulture, mainly to improve the use efficiency of water and fertilizers, particularly in countries with limited water resources. Fertigation technology offers more possibilities to exploit the physiological and genetic potential of a given plant than conventional irrigation and fertilization practices. The technique can reduce costs by combining water and fertilizer application, and can be combined also with directed application of plant protection agents (chemigation). Nutrient and water use efficiency may be improved by local application, close to the root system, according to plant needs. Moreover, this may help to reduce nitrogen losses through leaching and evaporation. However, apart from the obvious nutritional advantages, there are also clear indications that certain nutrients perform additional functions as signals that trigger plant growth and development. This may offer largely uninvestigated opportunities to improve application techniques in fertigation systems. To optimize the exploitation of crop potentials, the increasing background knowledge on these processes at the molecular and physiological level has to be better integrated into practical applications.

This report presents three case studies on non-nutritional fertigation effects as examples of approaches with prospects for directed manipulation of plant growth and development.

Urea phosphate for induction of plant earliness in vegetable production

In horticultural practice, accelerated plant development and, particularly, earlier flowering has been reported with urea phosphate (UP) than with the mono-ammonium phosphate (MAP), used in fertigation systems for vegetable production on calcareous soils (Jokinen et al., 2003). Therefore, the objective of this study was to compare UP and MAP fertilizers. Effects on plant development, nutritional status and changes of rhizosphere chemistry in the fertigation zone, induced by highly localized fertilizer application, were investigated in a greenhouse study with cucumber (Cucumis sativus L. cv. Vorgebirgstrauben), grown in rhizoboxes on a calcareous Loess sub-soil (pH 7.5) during a 68-day culture period, with cumulative N, P and K applications per plant of 0.53, 1.05, and 2.22 g, respectively.

Plant dry matter production did not differ significantly between the MAP and UP treatments. However, UP application accelerated plant development as expressed in root growth, leaf development and earliness of flowering. Moreover, the ratio of female/male flowers was increased by UP fertigation (Fig. 1). These findings suggest the involvement of ethylene as a hormonal factor for female sex determination in cucumber (Yamasaki and Takahashi, 2003).

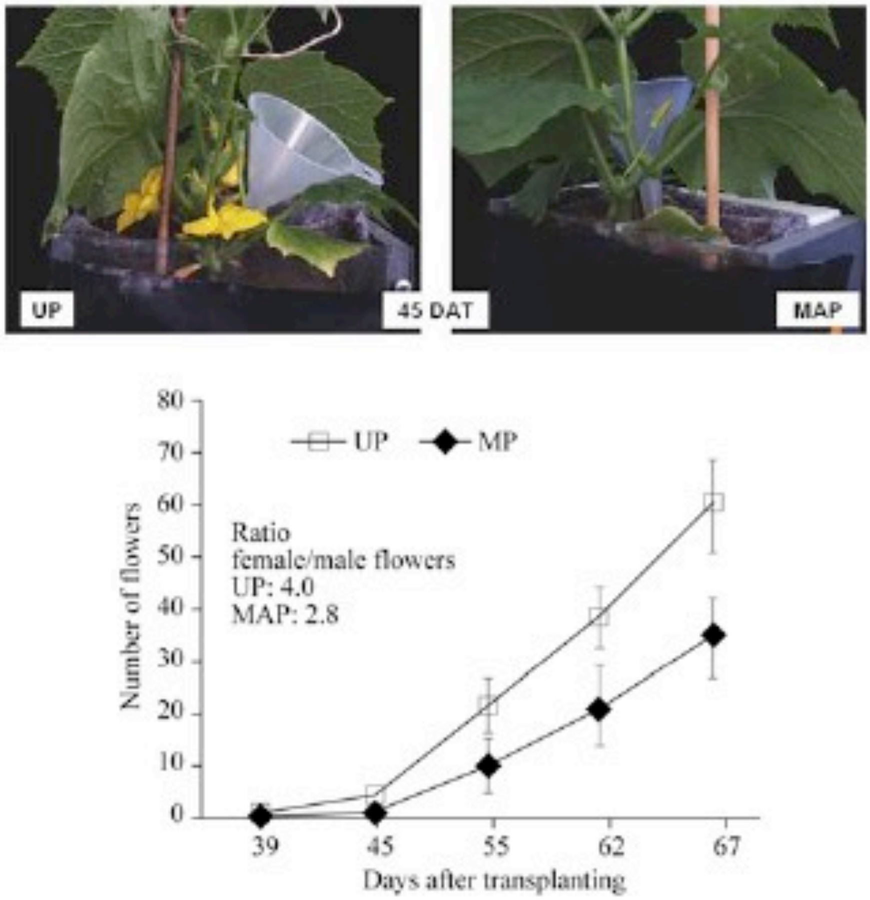

Fig. 1. Flower development and female/male ratios of cucumber flowers (cv. Vorgebirgstrauben), grown on a calcareous Loess sub-soil with UP or MAP fertigation.

The observed effects on "plant earliness" could not be attributed to any differences in the nutritional status of macro- (N, P, K, Ca, Mg) or micro-nutrients (Fe, Zn, Mn, Cu). However, in both treatments, shoot concentrations of Zn were in the critical range, probably related to low levels of available Zn in the calcareous Loess subsoil (Table 1).

Table 1: Concentrations of macro- and micro-nutrients in the shoot tissue of cucumber (cv. Vorgebirgstrauben), at 68 days after transplanting to soil culture on a calcareous Loess sub-soil, with UP or MAP fertigation.

Nutrient	UP	MAP	Adequate range
	----------------------------- %	------------------------------	
N	3.8a	4.1a	2.5-5.0
P	0.8a	0.8a	0.2-0.6
Mg	1.1a	1.1a	0.3-0.6
K	3.6a	3.8a	2.0-6.0
Ca	3.9a	3.8a	1.0-2.0
	------------------- mg/kg	dry matter----------------------	
Cu	12.7a	11.4a	5-10
Mn	43.3a	42.8a	100–200
Zn	29.6a	24.6a	50-150
Fe	73.6a	71.7a	30-150

Continuous application of the UP fertigation solution (pH 2.9) persistently lowered the soil pH in the fertigation zone, even in the strongly buffered calcareous soil. No comparable effects were observed in the MAP (pH 5.1) treatments, suggesting that continuous supply of the UP fertigation solution exceeded the buffering capacity of the soil in the fertigation zone after prolonged application cycles. At the same time, root-induced acidification was observed also, at the rhizoplane and in the rhizosphere soil of the UP treated plants; this may indicate preferential ammonium uptake and delayed nitrification in the UP treatments. Adjustment of the UP solution pH from 3.0 to 4.5 or 7.0 resulted in a lower rate of flower development, comparable with that in the MAP treatments (Fig. 2).

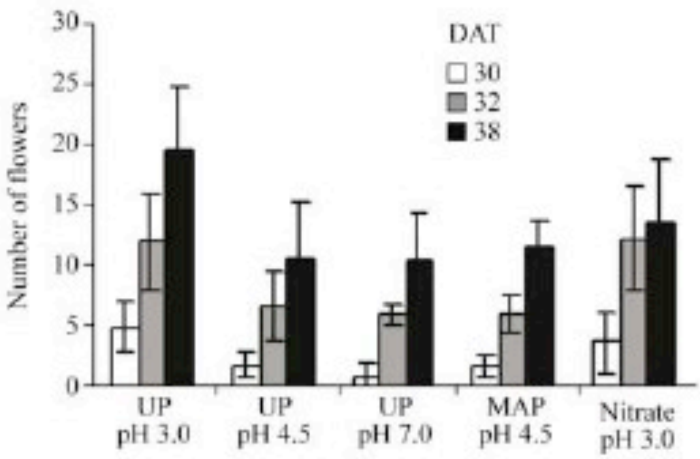

Fig. 2. Flower development of cucumber, grown on a calcareous Loess subsoil, as affected by the pH of the fertigation solution.

These findings suggest a key role for the fertigation solution pH in triggering plant developmental changes. Repeated application of the acidic UP-fertigation solution, exceeding the soil buffering capacity, may impose a sort of localized stress treatment on the part of the root system in the fertigation zone, since the root system is physiologically adapted to high soil pH. Repeated exposure to this treatment may induce a root-to-shoot signal, which stimulates generative growth.

Modulation of shoot growth by the form of the N supply

The availability and the form of the nutrient supply, especially of nitrogen, has a strong impact on plant growth and development. Nitrate in soils has not only nutritional functions, but also may act as a mobile signal molecule that helps plant roots to localize patches of less mobile nutrients, liberated, e.g., from “hot spots” of organic matter. Nitrate triggers increased formation of lateral roots in these nutrient-rich patches, via auxin signalling and activation of MADS-box transcription factors (Zhang et al., 1999). Proliferation of lateral roots in zones with high levels of nutrients may also be an important factor for exploitation of the highly localized nutrient supply in fertigation systems.

Apart from its role in adaptive regulation of root growth, nitrate seems also to have significant functions as a signal that triggers shoot development (Walch-Liu et al., 2000). In various plant species (tobacco, tomato, Arabidopsis, etc.) it has been demonstrated that removal of nitrate from the growth medium leads to inhibition of shoot growth (Fig. 3).

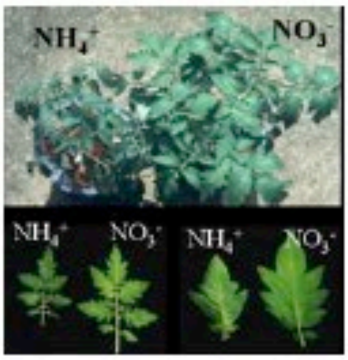

Fig. 3. Shoot and leaf morphology of tomato, as affected by the form of the N supply (2 mM NH_4^+ versus 2 mM NO_3^-).

This holds true not only for conditions of N deficiency; it occurs even when N limitation is avoided by application of NH_4^+ or other alternative N sources (urea, amino acids), and when the toxic effects of ammonium nutrition are suppressed by moderate application rates (maximum 2 mM N) and pH buffering of the culture substrate (Fig. 3).

In tomato, inhibition of leaf expansion is a rapid response, detectable within 6-8 h after removal/replacement of NO_3^- in the growth medium (Fig. 4a, b); it probably results from decreased root-to-shoot translocation of cytokinins, which is already detectable after 2 h (Fig. 4c, d). Similarly to cytokinins, root-to-shoot transfer of abscisic acid (ABA) also serves as an important signal for down-regulation of shoot growth under various stress conditions (e.g., drought, salinity, soil compaction), and it rapidly declines in the absence of nitrate (Fig. 4 e, f), suggesting that limitation of the supply of cytokinins to the shoot tissue is the primary inhibitory signal (Rahaju et al., 2005). However, in long-term studies, the absence of nitrate also induced a secondary increase of ABA translocation to the shoot. Preliminary studies on gene expression suggest that in

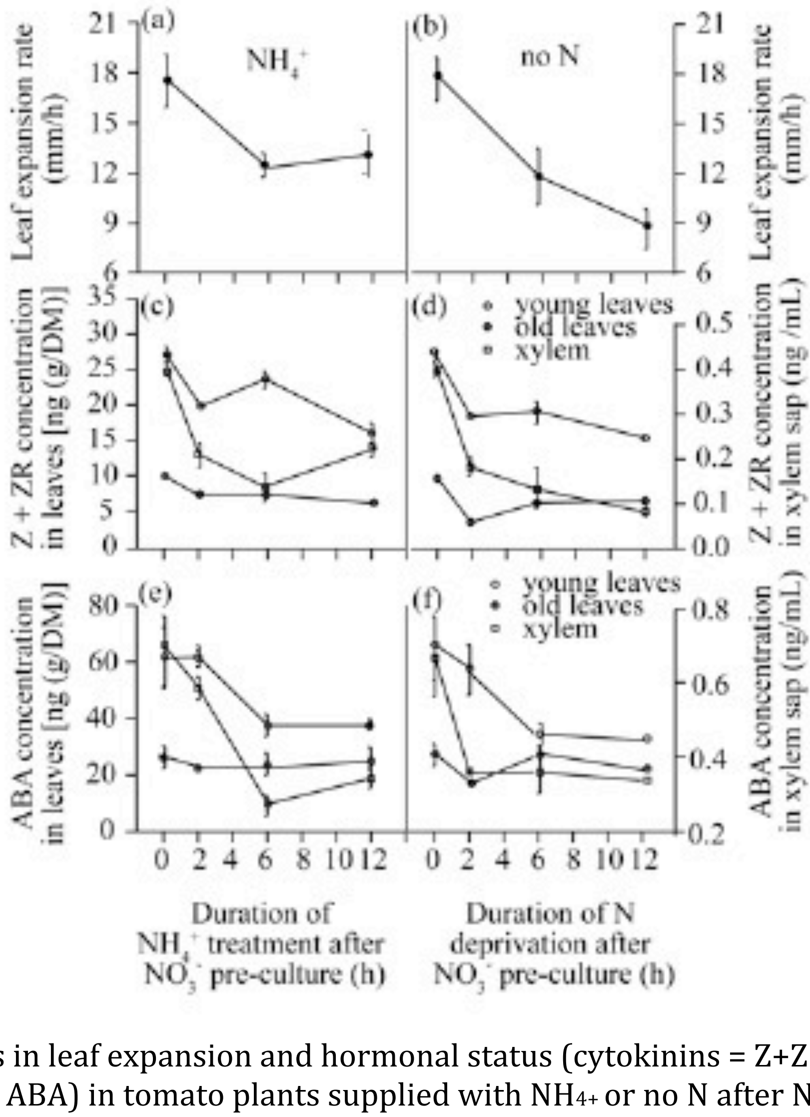

Fig. 4. Changes in leaf expansion and hormonal status (cytokinins = Z+ZR and abscisic acid = ABA) in tomato plants supplied with NH_4^+ or no N after NO_3^- preculture.

the presence of nitrate there is a cytokinin-induced up-regulation of the cell-wall expansins involved in cell expansion and of D-cyclins involved in cell cycle control and cell division (Fig. 5).

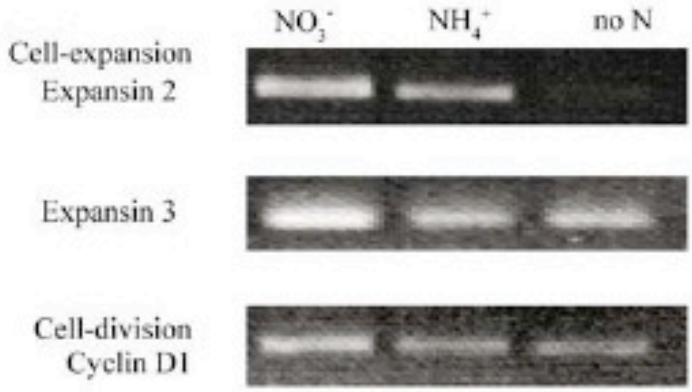

Fig. 5. Dependence on the form and level of N supply, of the expression of genes involved in cell expansion (expansins) and cell cycle control (cyclin D1) in tomato leaves (Northern analysis).

However, cytokinin-dependent regulation of shoot growth via nitrate supply is not restricted to leaf expansion; it also includes effects on shoot apical dominance. In tomato, outgrowth of lateral shoots can be reduced by increasing the NH_{4+}/NO_{3-} ratio (Fig. 6 and 7), and effect that probably is mediated by an increased auxin/cytokinin ratio in the shoot tissue that arises because the reduction in cytokinin translocation from the roots promotes apical dominance of the main shoot (Rahaju, 2003). This could offer an opportunity to manipulate fruit size in tomato culture by modifying the form and ratio of the N supply (Fig. 6).

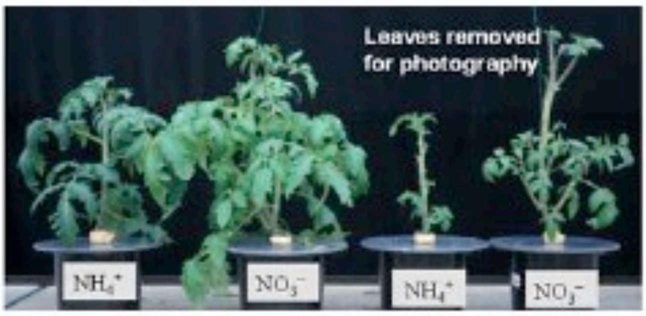

Fig. 6. Fruit development and formation of lateral shoots in tomato grown in hydroponic culture with different forms of N supply.

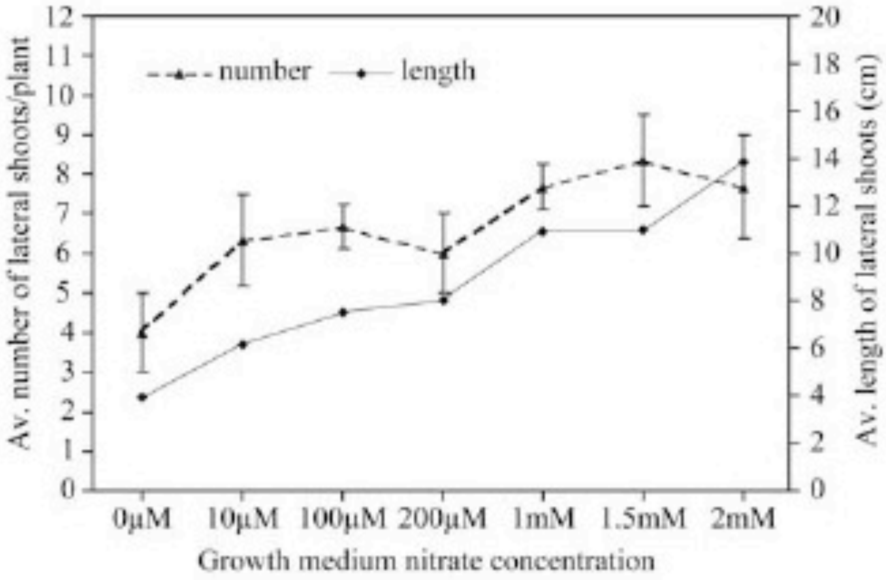

Fig. 7. Outgrowth but not the number of lateral shoots is stimulated by increasing the NO_3^-/NH_4^+ ratio in the hydroponic growth medium of tomato (total N supply = 2 mM, x-axis indicates the concentration of the NO_3^- supply, remaining N was supplied as NH_4^+).

The biomass yield of tomato fruits was only marginally affected by the form of the applied N. However, a solely NH_4^+ supply led to impaired fruit quality, expressed as higher incidence of Ca deficiency-induced blossom end rot, and lower concentrations of malate and citrate in the fruits (Table 2; Rahaju, 2003). Modifications of the NH_4^+/NO_3^- ratio and of the timing of the N supply could be employed to overcome these limitations and also to manipulate, e.g., malate/citrate ratios (Table 2).

Table 2. Incidence of Ca deficiency-induced blossom end rot, organic acid concentrations in fruits, fruit biomass and fruit number in tomato, grown in buffered nutrient solution as affected by the form of N supply (Rahaju, 2003).

N supply (2 mM)	Blossom end rot	Malate (fruit DM)	Citrate (fruit DM)	Fruit DM	Fruit number
	%	---------- mg/g	----------	g	No./plant
NO_3^-	0	20.5±1.1	22.7±1.2	58.2±1.5	28.5±1.5
NH_4^+	12.4±0.9	5.3±1.5	14.3±1.8	50.0±0.9	24.0±1.5

In accordance with the same principle, deep placement of urea-based fertilizers close to the roots is used to regulate tillering in barley and wheat (Fig. 8), in order to optimize yield by avoidance of mutual shading and competition among individual tillers (Bauer, 2004).

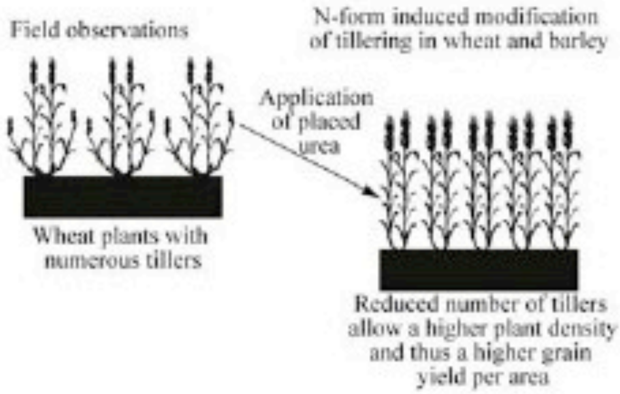

Fig. 8. Reduction of tillering in wheat and barley by deep-placement of urea-based fertilizers.

Induction of off-season flowering in lychee by short-term water or micro-nutrient deficiency stress via controlled fertigation

A widespread problem in lychee (Litchi chinensis Sonn.) production in northern Thailand (Fig. 9) is irregular annual fruit set (alternate bearing) as a consequence of inadequate low temperatures during December and January.

Fig. 9. Lychee production in northern Thailand.

In some tropical and subtropical fruits, off-season flowering can be induced by treatments with certain chemicals such as paclobutrazol (Mango) or $KClO_3$ (longan) but these compounds are ineffective for lychee. Because of water scarcity, micro-irrigation systems are of increasing interest for production of subtropical fruits, such as lychee.

A significant contribution to water saving under field conditions was achieved by using the partial root drying (PRD) technique, which restricts water application to parts of the soil surface around the trees. Under controlled conditions in split root culture vessels with divided root systems, PRD treatments to one half of the root system not only reduced water consumption but also induced flowering (Fig. 10).

Fig. 10. Induction of flowering by partial root drying treatments (PRD) to one half of the root system in young lychee trees grown in a split-root soil culture system.

Against expectations, B and Zn deficiency also induced off-season flowering in lychee seedlings (Fig. 11). The drought stress signal to one part of the root system may result in a decreased cytokinin content in buds, because of the increased root-to-shoot translocation of the cytokinin antagonist, abscisic acid. Boron and zinc deficiency can lead to a reduction of polar auxin transport from shoot apices (Wang et al., 2006), similar to the effects caused by application of synthetic auxin transport inhibitors such as TIBA (Fig. 12). A common result of all these treatments is a high auxin/cytokinin ratio in apical parts of the shoot, which may be involved in flower induction.

However, Stern et al. (2003) reported stimulation of flowering and increased cytokinin concentrations in the xylem sap of lychee under moderate drought stress, which may be attributed to reduction of the transpiration stream because of ABA-induced stomatal closure.

Fig. 11. Zinc deficiency-induced flowering in young lychee trees grown in hydroponic culture.

These alterations of hormonal balances may induce, or at least modulate signalling of flower development in subtropical fruit trees. Therefore, fertigation systems might offer an opportunity for directed application of localized stress treatments to induce off-season flowering in lychee orchards or, at least, to improve flower induction at marginal low temperatures. However, the practicability of such a practice under field conditions, in terms of irrigation intervals and strength and duration of stress treatments, remains to be evaluated.

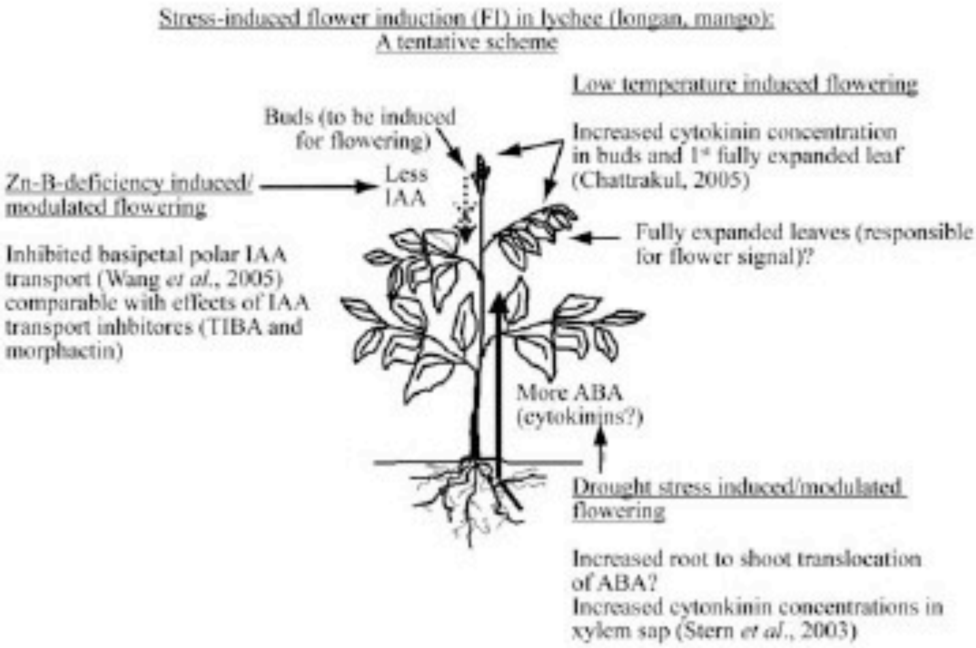

Fig. 12. Hypothetic model for stress-induced alterations of hormonal balances, that induce off-season flowering in tropical fruit trees.

Conclusions

The presented case studies clearly demonstrate that fertigation offers the potential to manipulate plant growth and development, independently of purely nutritional effects. In all the presented studies, changes in phytohormones played a decisive role in regulation of plant development to achieve an earlier and higher yield. Thus, better knowledge of phytohormonal regulation of plant growth and development could help to generate better, innovative fertigation strategies in crop production. The aim in presenting these case studies was not to give ready-to-use recipes, but rather to stimulate and encourage such a development for the benefit of growers.

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Fertigation in Greenhouse Production

Wim Voogt

Wageningen University and Research, Division Glasshouse Horticulture,
P.O. Box 8, 2665 ZG Bleiswijk, The Netherlands. E-mail: wim.voogt@wur.nl.

Abstract

Glasshouse horticulture offers possibilities for full process control; nevertheless it is faced by low fertiliser efficiency. Therefore, in areas with a high density of greenhouses, the discharges of N and P contribute significantly to ground- and surface-water pollution. To reduce the environmental impact, the Dutch Government has introduced specific legislation. Since fertigation is common practice with soil-grown crops, improvements in both irrigation strategies and nutrient supply are required. The uneven distribution of sprinkler systems, crop transpiration, and salt accumulation caused by poor water quality constitute bottlenecks. Reuse of drainage water and model-based systems in which irrigation and fertilisation strategies are linked to crop demand provide the best prospects for improving sustainability. Additional improvements could be achieved through reduction of the current N and P target values for the root environment. However, a change in the growers' attitude towards current irrigation and fertilisation strategies is indispensable.

Keywords: fertiliser, irrigation, nitrogen, phosphate, pollution, fertigation model.

Introduction

In general, greenhouse crops are grown intensively. As the mineral uptake is proportional to the total yield, the high physical production levels involve high fertiliser inputs, and the annual fertiliser application is eight to ten times as great as that for open-field vegetable crops (Sonneveld, 1993). Apart from the high crop demand, the high fertiliser inputs are also believed to be necessary to maintain high osmotic pressure levels in the root environment, in order to prevent lush growth and to enhance product quality (Sonneveld, 2000). However, these high fertiliser applications and the high levels in the root environment cause serious leaching and entry of N and P into ground and surface water (Wunderink, 1996).

The accurate control over many processes, and the absence of natural precipitation in protected cultivation offer ample possibilities to improve the sustainability of growing process and techniques, in contrast with the situation presented by open-field cultivation of vegetables. However, a complicating factor is that the costs of fertilisers and water in these intensive growing systems are virtually negligible compared with the total costs (Ruijs, 1995). In general, therefore, savings on these items do not form an incentive to implement concepts and measures regarding sustainability. Therefore, the Dutch government has decided to introduce legislation that includes some comprehensive regulations to reduce pollution.

Nutrient solutions

In present-day greenhouse horticulture fertilisers are applied mainly by fertigation, and specific fertigation programs have been developed for all crops (van den Bos et al., 1999). These are based on a basic nutrient solution, containing NH_4, K, Ca, Mg, NO_3, SO_4 (Table 1), with adjustments for specific conditions such as cropping stage, soil type, soil electrical conductivity (EC), etc. Furthermore, target values and limits are set for individual nutrients, and for Na, Cl, pH and EC levels in the soil (Table 2). For NH_4 the target value is set to zero, because the nitrification process develops very rapidly under greenhouse conditions and usually only negligible NH_4 is found.

Table 1. Composition of the basic nutrient solution for fertigation for some greenhouse crops, in mmol/L.

Crop	Nutrient solution					
	NH_4	K	Ca	Mg	NO_3	SO_4
	---------------------------- nmol/L ----------------------------					
Tomato	0.4	5.0	2.0	1.5	9.4	1.5
Cucumber	0.9	3.5	2.0	1.0	8.4	1.0
Sweet pepper	0.4	5.0	2.0	1.0	8.4	1.0
Rose	0.9	3.5	2.0	1.1	8.1	1.1

Table 2. Target values for nutrients and Na, Cl and EC for soil analysis (1:2 volume extract) (1).

Crop	K	Ca	Mg	NO3	SO4	Na	Cl	EC
	--------------------------------			mmol/L		----------------------------------		dS/m
Tomato	2.2	2.5	1.7	5.0	2.5	<4	<4	1.4
Cucumber	1.8	2.2	1.2	4.0	1.5	<4	<4	1.0
Sweet pepper	2.0	2.5	1.2	4.5	2.0	<4	<4	1.1
Rose	1.5	2.0	1.2	4.0	1.5	<4	<4	0.9

(1) According to Sonneveld and van den Ende (1971).

The differences between crops mainly concern the K/N, K/Ca and N/S ratios, but the total nutrient concentration, as indicated by the EC-value, may also differ. Micro-elements are not incorporated in the nutrient solution, as there is usually sufficient of them in the soil, the water, or the organic fertilisers used. An exception is B, which is a standard component of the nutrient solution when irrigation is with rainwater. Phosphorus is deliberately not part of the basic nutrient solution formulas, since it is much more effective and also less costly to place P in the soil via base dressings and soil tillage. Only in exceptional situations is P recommended in the fertigation.

For soil analysis the so called 1:2 volume extract is used (Sonneveld and van den Ende, 1971). Soil samples are evaluated by comparison with the target values, and the adjustments to the basis nutrient solution are recommended correspondingly.

The nutrient solution (whether adjusted or not) is converted into a fertiliser recipe for the preparation of tank stocks. For this purpose it is preferable to use single fertilisers, to match the supply of nutrients with the requirements for crop, water quality and soil conditions. In the case of irrigation water such as rainwater, that is low in Ca and/or Mg, the nutrient solution always contains these elements. As a consequence, separate stock tanks are necessary for Ca fertilisers and SO_4 fertilisers. Formulations with compound fertilisers often show a mismatch with the required ratios of individual elements and, as they do not contain Ca, additional calcium nitrate is required.

Environmental problems

In recent years a number of investigations of the water and nutrient balances in greenhouse-grown crops (Voogt, 2003) have clearly shown that there were large excesses of water and minerals, and that, consequently, the emissions of N and, to a lesser extent, of P to the environment were large (Tables 3 and 4). The problem of these low efficiencies can be summarized as follows.

High EC and nutrient level in the soil are necessary to meet the crop requirements at the high growth rates obtained under protected cultivation (Sonneveld, 1993).

High EC levels are essential for product quality improvement (Sonneveld, 1988).

Irrigation is mainly through overhead sprinkler systems, which are characterized by uneven water supply, which necessitates over-irrigation (Heemskerk et al., 1997).

It is common practice for growers to over-irrigate the crop. (Voogt, 2003).

In soil-bound crops surface water is often used, and since it contains rather high salt concentrations, leaching is necessary to prevent salinity problems (Sonneveld, 1995).

The costs of fertilisation are insignificant compared with the total production costs in greenhouse cropping (Ruijs, 1992).

Table 3. Annual water and mineral use of some glasshouse crops.

Crop	Water	N	P	K
	M^3/ha	--------------------	kg/ha	--------------------
Tomato	12,950	1,150	205	1,410
Cucumber	10,400	980	240	1,100
Rose	11,500	990	110	910

Table 4. Water and nitrogen efficiency rates for some crops.

Crop	Water	Nitrogen
Tomato	0.80	0.55
Cucumber	0.79	0.54
Sweet pepper	0.88	0.61
Rose	0.78	0.60
Chrysanthemum	0.65	0.52

Improvements

Fertigation is an excellent method to improve the sustainability of greenhouse production, since it enables both the water movement in the soil and nutrient supply to be controlled. Adjustment of the irrigation strategy is necessary in the first place because vertical transport of water in the soil is the driving force behind mineral losses to the groundwater table or the surrounding surface water.

The success of a fertigation strategy will depend on the variations within the greenhouse, which are caused by the nonuniform distribution of the irrigation system and differences in crop transpiration and evaporation (Fig. 1).

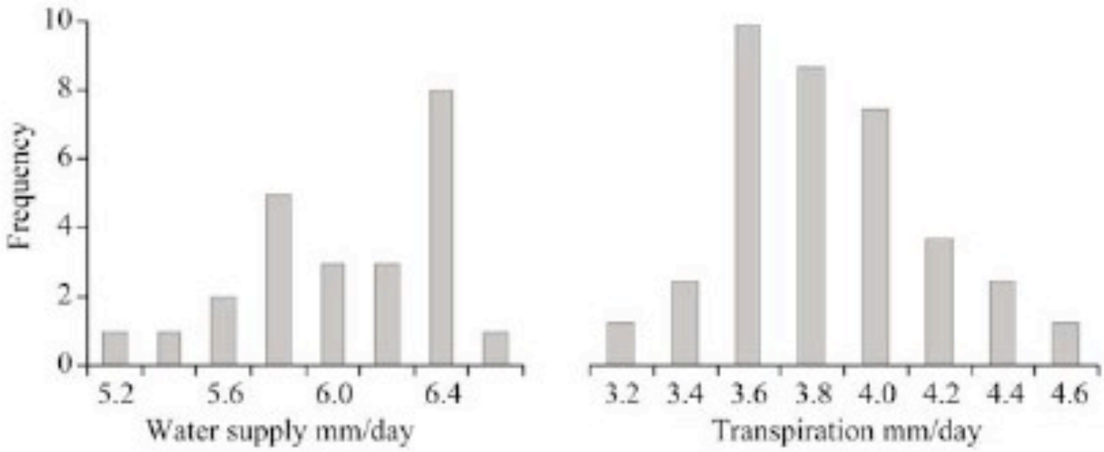

Fig. 1. Frequency distribution of the water supply from drip irrigation, and the water uptake, measured at 32 random spots in a greenhouse tomato crop (van den Burg et al., 1987).

Heemskerk et al. (1997) listed the distribution variations in a number of sprinkler systems and configurations that are used in practice. With modern wide-broadcasting rotating sprinkler systems the CV (coefficient of variation) can be as low as 5–8%, provided that the appropriate configuration of pipes and emitters is correctly installed and the system is operated at the right pressure. They also found that the CV of new, initially clean systems will increase rapidly, therefore proper filtration and maintenance of the system is important. The same is true of drip irrigation systems, which are widely used for fertigation in greenhouses (van den Burg, 1991).

The water buffering capacity of the soil plays a role in this variation. Moreover, lateral diffusion and horizontal rooting may partly even out spatial variations in moisture content. Assinck and Heinen (2002) simulated root development and water uptake under various conditions of unevenness of irrigation applied to sequential chrysanthemum crops, and concluded that no problems with water stress are to be expected up to a CV of 12%. Moreover, capillary rise and deep root development will supplement the water supply to the crop. These results were found in a practical experiment in which some growers successfully reduced the irrigation surplus (i.e., the irrigation supply minus the calculated evapo-transpiration) to zero or even to negative values, and found that the resulting nutrient losses did not cause any decline in crop performance (Voogt et al., 2002). In this particular case, the water demand by the crop was probably made up from groundwater. Nevertheless this method is not a sustainable solution, because in the long run there will be a threat of salinity problems, since the groundwater always contains salts at higher concentrations than the plant uptake capacity (Sonneveld, 1993). Because of capillary rise, ions will inevitably be transported upwards and so will increase the salt concentration in the topsoil. Eventually severe leaching of the soil is unavoidable, probably with more salts leaching out than would occur under regular low-intensity leaching while the salts are accumulating.

An obvious solution for the problem of mineral emission is the reuse of drainage water, as in the closed-system concept applied in soilless culture (Voogt and Sonneveld, 1997). The majority of protected cultivation in the Netherlands is situated in polder areas where there is a high ground water level. Almost all greenhouses are therefore equipped with drainage systems. These are usually closed systems, with a pump to lower the groundwater level in the greenhouse soil and to drain off the surplus water. As a result of the forced lowering of the groundwater level, the hydrological situation is sometimes complex. The net drainage flow is a combination of percolation of the irrigation surplus from the peripheral soil, seepage from surrounding surface waters and from the groundwater, and leaching to the groundwater. The interpretation of drainage quantity and quality is therefore sometimes difficult. This was illustrated by Voogt (2003), who examined a set of data from 30 greenhouses and showed that it was impossible to correlate the N leaching by drainage with the irrigation or the fertilisation (Fig. 2).

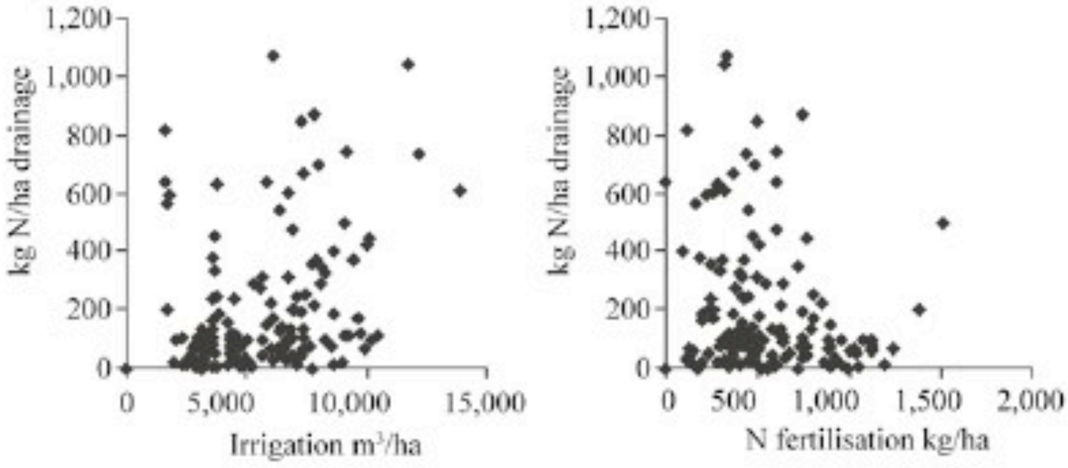

Fig. 2. Relation between the yearly total irrigation (left panel) and the total N fertilisation (right panel) and the total N in the drainage, as monitored in 30 greenhouses during 1996 – 2000 (Voogt, 2003).

However, because of the complex hydrology, mentioned above, a true closed system, based on the standard configurations of drainage systems in soil is virtually impossible. There will always be the risk of diffuse leaching to the shallow groundwater (Boers, 1996). Furthermore, seepage of surface water or adjacent groundwater into drainage pipes must also be considered. Sometimes this causes a quantitative problem (too much drainage in the winter period), and quite often a qualitative problem because of excessive concentrations of ions such as Na, Cl or SO_4. The creation of a closed system, by installing an impermeable layer in the soil is only practicable if the soil layer is deep enough to create sufficient hydraulic pressure to prevent air problems in the root zone. In practical trials, it was shown that depths of 40 cm were insufficient, because of serious problems with soil compaction and air and moisture management (van Emmerik, 1994). Apart from the technical problems, the method is unfeasible from the economic point of view (Ruijs, 1995).

Fertigation model

Systems in which the water and fertiliser supplies are continuously attuned to the demands of the crop will have the best prospects for improving sustainability of soil-grown crops; the “fertigation model” is such a system

(Voogt et al., 2000). The basic principle of this system is that supplies of water and nutrients are determined by the crop demands, which are determined by model calculations. The algorithm for irrigation is based on an evapotranspiration model (de Graaf, 1999) and it contains parameters for irradiation, heating, developmental stage of the crop, and crop- and greenhouse-specific factors. The nutrient uptake is considered to be closely connected with the water uptake and is calculated as uptake concentration, which is derived from empirical data of the average total nutrient and water uptake. For short-term crops such as radish, lettuce and chrysanthemums, one concentration is maintained for the whole cropping period, whereas for long-term crops, such as tomato and sweet pepper, the concentration changes in accordance with the changes in the cropping stage. Fig. 3 presents an example of a long-term tomato crop. Seasonal effects, related to the change in irradiation should be particularly taken into account. Sonneveld and van den Bos (1995) clearly showed with radish that the uptake concentrations of all nutrients in winter (under poor light condition) were four to five times higher than in summer (under abundant light conditions).

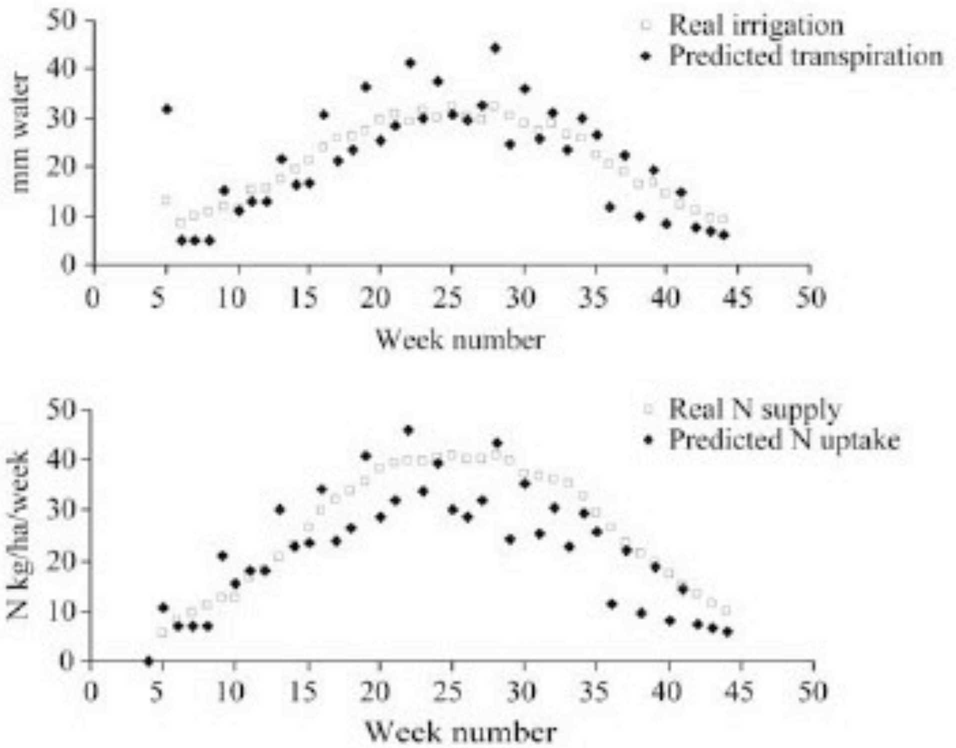

Fig. 3. Predicted irrigation (top) and N supply (bottom) compared with the real irrigation and N-supply in a commercial tomato crop, as recommended by the fertigation model.

To control the model, the moisture content of the soil is measured by means of tensiometers or FD sensors. Feedback on the supply of nutrients can only be obtained through regular soil analysis.

The model was tested in 1999 with satisfactory results (Voogt et al., 2000). Compared with the standard fertigation schedules of the individual growers, the water and N surplus in the test nurseries could be reduced significantly (Fig. 4). However, the results also indicate that zero leaching is difficult to achieve.

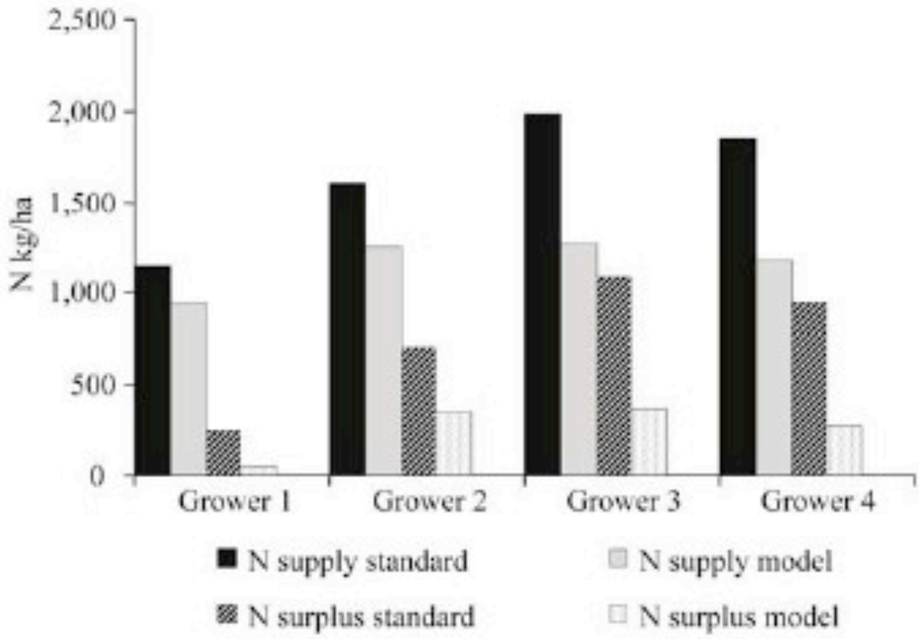

Fig. 4. The yearly N surplus in greenhouse crops of four growers after application of the fertigation model, in comparison with their standard fertigation strategy.

This method enables nutrient leaching to be reduced substantially. In addition to the measures mentioned previously, reduction in the N and P buffer in the soil, i.e., the target values for soil analysis, will improve the result. As already mentioned, the current recommendation system is based on an old concept. Fertilisation schedules were primarily meant to achieve and maintain certain target values in the soil, and it could be deduced from old research results that for the majority of the crops the target values could be reduced without any effect on yield or quality. It was interesting to see that van den Bos (2003) showed clearly that neither yield nor quality of lettuce was negatively affected by lowering the N target values and, consequently, the N supply (Table 5).

Table 5. The average soil mineral N, N supply, yield (average head weight, relative to treatment 1) and N uptake of four successive lettuce crops, in an investigation of lettuce in soil, with four target levels of soil N at the start of the crop (van den Bos, 2003).

Treatment	N target value (1)	Mineral N in soil (1)	N supply	Yield	N uptake
	-------- nmol/L --------		kg/ha	%	kg/ha
1	3	2.1	72	100	138
2	5	3.6	123	103	143
3	7	5.8	189	102	149
4	9	7.4	238	102	147

(1) Expressed as the N-min. concentration in the 1:2 volume extract in the top soil (0 - 25 cm depth)

Also with chrysanthemum, reduction in the N-soil buffer was shown to be possible without causing any problems (Voogt et al., 2002). Although the effects on leaching could not be determined in these experiments, one can imagine that a reduction of the N concentration in the soil would at least reduce the risk of N leaching. In specific crops for which the EC value is important for quality, the reduction in N supply must be compensated by application of other salts. For instance van den Bos (pers. comm.) has reported fertiliser trials with radish, in which N was successfully partly replaced by SO_4 and Cl.

van den Bos (2001) also found for P that the recommendation system could be adjusted; in long-term experiments with chrysanthemum and lettuce, he found that even with zero-P treatments there was no effect on crop performance (Table 6). This shows that the vast buffer of P built up in many years over-fertilisation in most greenhouse soils could deliver sufficient P. However, reduction in the P fertilisation will hardly contribute to improvement of the environment, since the leaching of P from greenhouse soils is already very limited. It was shown by Korsten (1995) that the P concentration in drainage water was low, even when the greenhouse soils have a high P content. This is mainly because of the high content of either Fe and Al or $CaCO_3$ in those soils.

Table 6. Results of a 3-year fertiliser trial with 13 successive lettuce crops. Average P-content in the soil expressed as: P in the 1:2 volume extract, Pw value and P-Al content, the P-fertiliser supply, yield (average head weight), P content and P uptake. Treatment 2 is the standard recommended value for P for this soil. (van den Bos, 2001).

Treatment	P supply	P (1:2)	Pw (1)	P-Al (2)	Yield	P cont.	P
	kg/ha	nmol/L	mg/L	mg/100 g	g/head	nmol/kg DM	kg/ha
1	0	0.03	48	122	320	186	641
2	340	0.07	73	133	331	214	739
3	680	0.11	101	146	330	231	789
4	1,020	0.16	132	152	331	242	825
5	1,360	0.22	162	165	332	248	848

(1) P in water extraction, expressed as mg P_2O_5 per liter dry soil
(2) P in extraction of Al-acetate, expressed as mg P_2O_5 per 100 g dry soil

All methods that focus on the reduction of leaching are only successful if water of excellent quality is used. Salinity is a serious problem in the greenhouse industry because of the absence of natural precipitation. Salinity threshold values found for greenhouse crops vary widely among crops and growing conditions (Sonneveld, 1988). Moreover, there is also a considerable interaction between salinity and the fertilisation of crops. It has been shown that when high osmotic pressures are required for certain crops and growing conditions, increasing the levels of nutrients or salts makes no difference. It even appears that in some situations, increased osmotic pressure caused by higher levels of NaCl show advantages above the same increase with nutrients (Adams, 1991). The recommended values for crops grown where there is high osmotic pressure in the soil solution therefore depend on the salinity level. Nevertheless, in spite of the required or acceptable increased salinity levels, water with too high a salt content will, in the long run, lead to salinity problems. In view of the aim of reduced leaching, standards for water quality were drawn up (Table 7).

Table 7. Water quality standards for fertigation with minimum leaching, with respect to salt sensitivity.

Salt sensitivity	EC	Na	Cl	Ca	Mg	SO_4
	dS/m	-----------------------		mmol/L		-----------------------
Sensitivity	<0.5	<1.5	<1.5	<2.0	<1.5	<2.0
Moderate	<1.0	<2.0	<2.5	<3.0	<2.0	<3.0
Tolerant	<1.5	<3.0	<4.0	<4.0	<2.5	<4.0

Conclusion

Because of the complexity of the hydrology of greenhouses, no correlation was found between the amount of irrigation or fertilisation and the quantity of nitrogen leached out by drainage water. Nevertheless, it is clear that the nutrient use efficiency of soil-grown greenhouse crops is low, and the current situation can, therefore, be characterised as unsustainable. Moreover, the intensification of production inevitably leads to further increases in N and P use. Obligatory re-use of drainage water is not applicable to soil-grown crops, because the diversity of hydrological situations makes it too complex. The most promising systems involves the supply of water and nutrients according to crop demand; such systems, like the fertigation model, use model calculations and feedback of soil moisture content. However, such a method can only be applied under restricted conditions. Spatial variations in water supply and crop transpiration should be as low as possible and the method requires irrigation water of perfect quality, to prevent salinity problems. Additional improvements are possible since it was evident that there is a gap between the recommended nutrient levels and the minimum levels for optimal growth. Thus, target values for N and P in the root environment can be reduced.

A complication in the introduction of systems that use reduced supply arises from the current attitude of growers towards irrigation and fertilisation. Since product quality and total yield are much more important to them than water and fertiliser costs, or environmental concerns, modern greenhouse production stimulates fertiliser use rather than reducing it. On the other hand, there is a strong influence from the market, which requires products to be grown under strict licensing conditions which, for instance strictly limit water and fertiliser use.

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Effects of Fertigation Regime on Blossom End Rot of Vegetable Fruits

Asher Bar-Tal, and Benny Aloni

Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, The Volcani Center, P.O. Box 6, Bet Dagan 50250, Israel.
E-mail: abartal@volcani.agri.gov.il.

Abstract

The relationships between blossom end rot (BER) of vegetable fruits and fertigation regimes are reviewed. Many fruit disorders are affected by nutrient deficiencies or unbalanced nutrition: BER, gold specks, green back, blotchy ripening, color spots, malformation, hollowness, and fruit cracking. Numerous studies have shown that BER is a mineral disorder and that its occurrence could be reduced by improving the supply of specific nutrients. The sensitivity of vegetable fruits to BER varies greatly among cultivars, environmental conditions and fertigation regimes. Some interactions between environmental conditions and fertigation regime are presented. The relation between BER and Ca nutrition is described and discussed in detail. The possibility that Mn may also play a role in the development of BER is discussed.

Keywords: blossom end rot, calcium, magnesium, manganese, oxidative stress, potassium.

Introduction

The aim of the present mini-review is to describe the relationships between blossom end rot (BER) of vegetable fruits and the fertigation regime. Blossom end rot is one of the main mineral disorders affecting tomato and pepper fruits; it reduces marketable yield, especially during hot and dry seasons, by up to 50% (Roorda van Eysinga and van der Meijs, 1981; Winsor and Adams, 1987). More than 50 papers that deal with this disorder have been published in the last 5 years in scientific journals cited by the ISI. Environmental and management factors that enhance or reduce the occurrence of BER are well known and are being studied. During over 60 years of research, BER occurrence has been related to calcium deficiency in the fruit and in the defective tissue; it has been related to reduced translocation of calcium to the fruit tip under stress conditions, and is therefore referred to as a “calcium-related disorder” (Ho et al., 1993; Ho and White, 2005; Marcelis and Ho, 1999). The majority of studies have identified a localized Ca deficiency in the distal fruit tissue as the primary cause of BER (Ho and White, 2005). However, in many studies no correlation was found between BER and Ca concentration in the fruit. On the basis of a thorough review of the literature, Saure (2001) concluded that calcium deficiency per se may not be the only detrimental factor, and that additional "metabolic stress factors" might be involved. In the present paper we will describe observations that support this concept, others that question it, new ideas on the mechanism of BER, and what information is required to advance our understanding of this disorder.

Calcium uptake and translocation

Most soils, except very acidic ones, contain high Calcium concentrations. The Ca concentration in the soil is usually 10 times that of K, but the uptake of the former is usually lower (Kirkby and Pilbeam, 1984). Ca is a divalent ion and as the valence of ion increases the uptake decreases (Marschner, 1995). In contrast to that of K, Ca uptake is limited to the very young section of the roots and the mineral is transported toward the xylem mainly by apoplastic flux, with little translocation in the phloem (Hanson, 1984; Jeschke and Pate, 1991). Calcium deficiency in the fruit may be caused by inadequate Ca uptake, caused, in turn, by low Ca concentration in the solution and by antagonism with other cations (K^+, NH_4^+) (Wilcox et al., 1973; Marti and Mills, 1991; Bar-Tal and Pressman, 1996; Bar-Tal et al., 2001b, c; Ho and White, 2005). The major pathway for Ca supply to the fruits is by direct transport from the roots via the xylem (Wiersum, 1966; Chiu and Bould, 1976; Ho et al., 1993). Calcium uptake and transport in the plant is strongly dependent on transpiration, therefore, the Ca concentration in transpiring organs such as leaves is higher than that in non-transpiring organs such as flowers and fruits (Clarkson, 1984; Hanson, 1984). The main cause for Ca deficiency in fruit is its low mobility in the plant from matured tissues to young ones (Ho and White, 2005; Saure, 2005).

Solution Composition Effects

Ca, K, Mg and NH_4

Numerous studies have shown that BER in tomato fruits can be induced by low Ca (e.g.: Maynard et al., 1957; Adams and Holder, 1992; Chiu and Bould, 1976; de Kreij, 1996; Taylor et al., 2004). We found that increasing the Ca concentration in the irrigation water was an effective means to reduce the incidence of BER in pepper fruits (Table 1), and that it enhanced the Ca content in pepper fruitlets (Table 2).

Table 1. BER occurrence (%) in pepper fruits as affected by three solution Ca concentrations and three irrigation frequencies (after Bar-Tal et al., 2001d).

Irrigation frequency (day^{-1})	C_{Ca} (ppm)			
	50	100	150	Mean
	------------------------- % -------------------------			
3	40	37	33	37a
6	44	40	39	41a
12	37	27	32	32b
Mean	40a	35b	35b	

P(f)Ca = 0.018, P(f)irrigation >0.001, P(f)irrigation*Ca = >0.1

Calcium deficiency in plants grown in sufficient Ca levels results mainly from inadequate distribution in the plant organs (Wiersum, 1966; Clarkson, 1984; Ho et al., 1987, 1993; Marcelis and Ho, 1999). Therefore, it has been suggested that spraying Ca salts directly onto the fruitlets could be an effective means to eliminate BER. Ho and White (2005) obtained a reduction in the incidence of BER in tomato fruits by spraying the fruitlets with Ca solution, and similar results were obtained by other researchers.

Table 2. Ca concentration in fruitlets (mg/g) as affected by three solution Ca concentrations and three irrigation frequencies (after Bar-Tal et al. 2001d).

Irrigation frequency (day^{-1})	C_{Ca} (ppm)			
	50	100	150	Mean
	------------------------- mg/g -------------------------			
3	1.58	1.85	1.91	1.78b
6	1.73	2.00	2.17	1.97a
12	1.94	1.99	2.03	1.99a
Mean	1.75b	1.95a	2.04a	

P(f)Ca = 0.001, P(f)irrigation >0.1, P(f)irrigation*Ca = >0.1

The composition of the soil solution may influence plant Ca uptake, because of antagonism with other cations, mainly K^+, Mg^{2+} and NH_4^+. Bar-Tal et al. (2001a) reported that increasing the Ca concentration from 0.5 to 4.0 mmol/L resulted in a significant increase in Ca concentrations in the leaves and petals of three rose cultivars. By using K and Mg as the compensating cations, instead of Na, they reduced Ca concentrations in the leaves and petals of the flowering stem of rose (Bar-Tal et al., 2001a).

Use of a high K/Ca ratio in fertilizing tomato plants has been reported to increase the proportion of tomato fruits showing BER (van der Boon, 1973; Taylor et al., 2004). Bar-Tal and Pressman (1996) found that the occurrence of BER increased steeply, from 6.8 to 25.5% when they increased the potassium concentration in a hydroponic system from 2.5 to 10.0 $mmol_c$/L at constant Ca concentration, whereas elevating the Ca concentration from 3.0 to 7.0 $mmol_c$/L reduced the occurrence of BER from 13.7 to 3.3% (Table 3). Increasing the K concentration from 2.5 to 10 mmol/L increased the K concentration in plant organs and the K uptake rate, but reduced that of Ca. However, Bar-Tal and Pressman (1996) found very poor correlations among the incidence of BER, the concentrations of Ca and K, and the K/Ca ratio, in ripe fruits, whereas, they found high correlation between the incidence of BER and the K/Ca ratio in the leaves.

Table 3. Effects of Ca and K concentration on the incidence of BER affected tomato fruits (number of fruits per plant) (after Bar-Tal and Pressman, 1996).

C_K	C_{Ca}	C_K/C_{Ca}	BER	Total
--------- $mmol_c$/L ---------			Number of fruits per plant	
2.5	3.0	0.83	5.7	83.9
5.0	3.0	1.67	11.3	82.7
10.0	3.0	3.33	22.9	89.8
5.0	7.0	0.71	2.8	84.7
$LSD_{0.05}$			8.0	12.0

Ca and Mg are both alkaline earth elements that are taken up by plants as divalent cations. Schwartz and Bar-Yosef (1983) found that the uptake rate of Ca by young tomato roots decreased as the solution Mg concentration increased. The effect of the Mg concentration on Ca uptake rate was through the value of the rate coefficient (K_m) in the Michaelis-Menten equation, whereas the maximum uptake rate (F_{max}) was not affected. Hao and Papadopoulos (2004) reported an increase in the incidence of BER-affected tomato fruits as the Mg concentration increased from 20 to 80 mg/L when the Ca concentration was 150 mg/L. When the Ca concentration was elevated to 300 mg/L changing the Mg concentration had no effect.

The nitrogen form is an important factor for plant development and yield. Increasing the N-NH_4:N-NO_3 ratio in the N fertilizer reduced the uptake of other mineral cations but increased the uptake of mineral anions by tomato (Kirkby and Mengel, 1967; Ganmore-Neumann and Kafkafi, 1980) and pepper (Marti and Mills, 1991), whereas Sarro et al. (1995) reported that ammonium reduced Ca and Mg uptake by pepper, but had no effect on K uptake. Bar-Tal et al. (2001c) reported that the uptake of Ca and K increased quadratically as the N-NO_3:N-NH_4 ratio increased, throughout the studied range of 0.25 to 4.0 (Fig. 1).

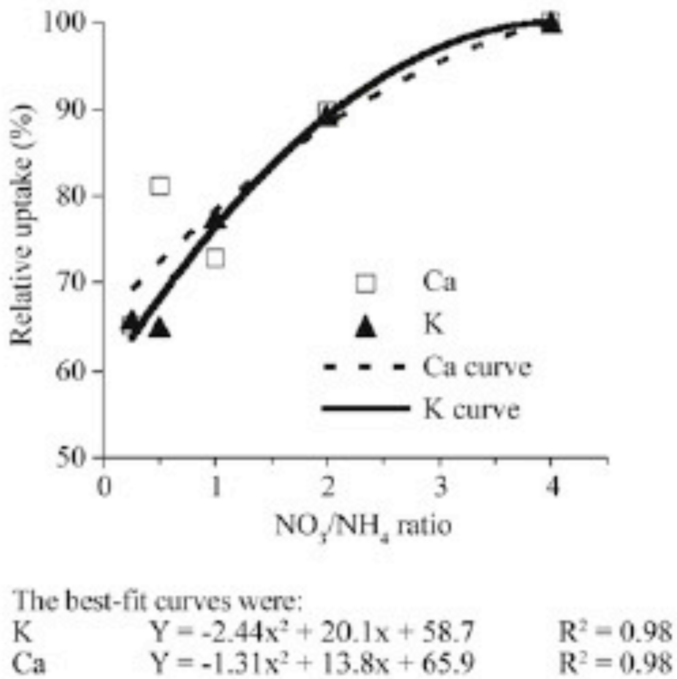

Fig. 1. Effect of NH_4/NO_3 concentrations ratio on K and Ca uptake (after Bar-Tal et al., 2001b).

Blossom-end-rot has been found to be affected by the N-NH_4:N-NO_3 ratio, through its effect on Ca concentration, in the fruits of tomato (Wojciechowski et al. 1969; Wilcox et al. 1973) and of pepper (Marti and Mills, 1991; Morley et al., 1993). The early stage of fruit development is the period that is most sensitive to Ca supply (Marti and Mills, 1991). Bar-Tal et al. (2001b) showed that the occurrence of BER in pepper fruits could be reduced by fertigation in which the nitrogen supply contained a low ammonium fraction (Fig. 2); they found that BER incidence was well correlated with the Ca content in young fruits. The concentration of Ca in mature pepper fruit was three times higher in the distal part of the pepper fruits than in the blossom end, and the effect of the N-NO_3:N-NH_4 ratio on Ca concentration was significant in each part (Bar-Tal et al, 2001b). Ho et al. (1993) reported that high radiation intensity, combined with NH_4 nutrition, increased the incidence of BER in tomato.

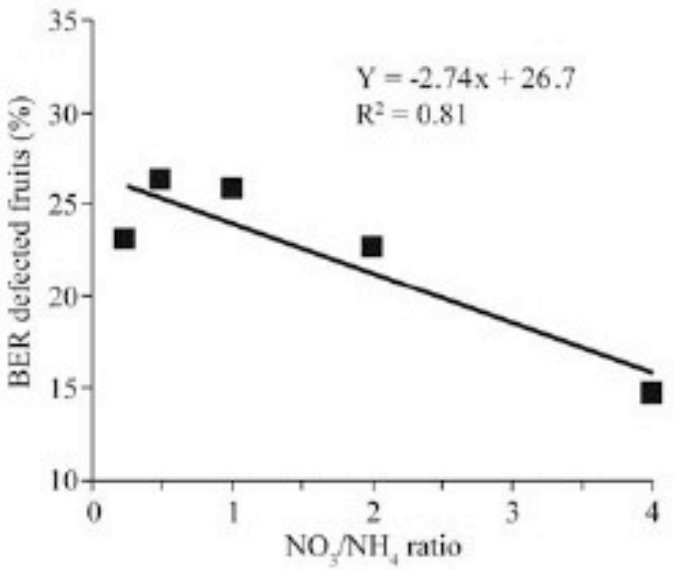

Fig. 2. Effect of NH_4/NO_3 concentration ratio on BER occurrence (after Bar-Tal et al. 2001b).

Salinity

Irrigation with saline water enhanced the occurrence of BER in tomato fruits (Ehret and Ho, 1986a; Adams and Ho, 1992; Adams and Holder, 1992). The occurrence of BER in pepper was found to increase dramatically when the EC increased above 1.0 dS/m (Sonneveld, 1979). Aktas et al. (2005) and Bar-Tal et al. (2003) reported that irrigation with saline solution caused a substantial increase in the percentage of BER-affected fruits, especially when the temperature increased during the spring and summer (Fig. 3).

The increase in the occurrence of BER-affected fruits under irrigation with saline water has been related to reduced Ca uptake and transport into the fruits (Ehret and Ho, 1986a; Adams and Ho, 1992; Adams and Holder, 1992). However, Aktas et al. (2005) found that irrigation with saline water that contained high Ca concentration had no effect on the concentration of Ca in BER-free fruits at their initial developmental stage, whereas the calcium concentration in the leaves slightly increased (Table 4). They also found that high salinity caused a substantial decrease in the concentration of manganese in both the fruits and the young leaves (Table 4). This finding led us to investigate the possible role of Mn in the development of BER in fruits.

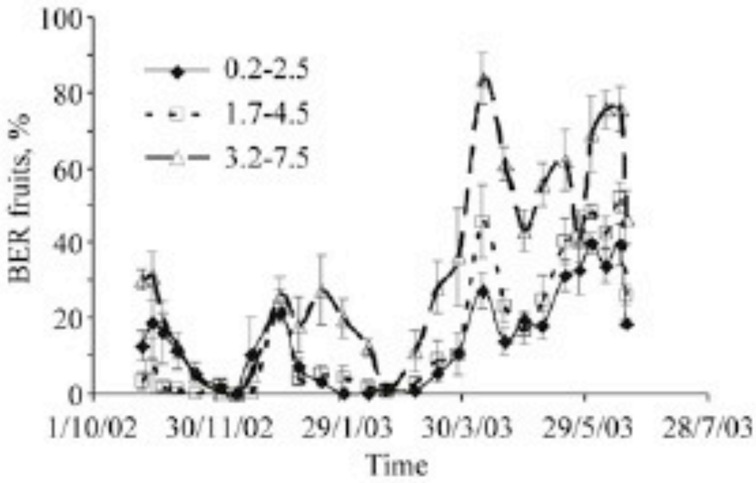

Fig. 3. Effect of salinity on the occurrence of BER (after Aktas et al. 2005).

Table 4. The effects of salinity on the dry matter content (DM) and concentrations of Ca and Mn in young fruits and leaves (after Aktas et al., 2005).

Salinity level ds/m	1.5		14.5		6.8	
	Fruit	Leaves	Fruit	Leaves	Fruit	Leaves
Dw (%)	4.45		4.87		5.34	
Ca (mg/g)	1.3	19.0	1.3	22.0	1.2	24
Mn (mg/kg)	41.3	283	32.1	214	20.1	61.0

Climate

Several studies have shown that the incidence of BER in tomato is lower under high daytime relative humidity (RH) than under low RH (Adams and Holder, 1992; Adams and Ho, 1993; Brown and Ho, 1993; Ho et al., 1993; de Kreij, 1996; Bertin et al., 2000). However, the opposite effect was found by Banuelos et al. (1985), and Tadesse et al. (2001) reported that increasing the RH of the air close to the fruit enhanced the incidence of BER in pepper. The effects of air temperature and humidity on BER incidence have been related to their impact on the supply of Ca to the fruit (Wiersum, 1966; Ho, 1989; Brown and Ho, 1993; Ho et al. 1993; Ho and White, 2005). It is well accepted that Ca translocation to plant organs is via the xylem, whereas that via the phloem is negligible (Clarkson, 1984; Hanson, 1984). This conclusion is based on measurements of xylem and phloem composition and on the fact that high-transpiring organs contain much more Ca than low-transpiring ones (Hanson, 1984; Baas et al., 2003). Therefore, Ca translocation and distribution in plant are controlled by environmental conditions that affect the transpiration and water status of plant organs (Wiersum, 1966; Brown and Ho, 1993; Ho, 1989; Ho et al., 1993). According to this concept one may expect that, providing that water supply is not a limiting factor, environmental conditions that enhance transpiration would increase the Ca concentration in all organs to the same extent. However, under environmental conditions that enhance transpiration, i.e., low RH and high temperature, the Ca concentration in the leaves increased whereas that in the fruit decreased (Ho, 1989; Adams and Holder, 1992; Ho et al., 1993). This contradiction has been attributed to competition for water between the leaves, which are high-transpiring organs, and the fruits or flowers, which are low-transpiring ones; competition that restricts Ca translocation to the latter (Wiersum, 1966; Ho et al., 1993).

Bar-Tal and Aloni (unpublished data) found that an evaporative cooling system (ECS) and shading reduced the occurrence of BER in pepper fruits during spring and summer (Fig. 4). Bar-Tal et al. (2006) found that the effect of the ECS and shading was probably due to reductions in fruit temperature and transpiration, which improved the ability of the plant to maintain the water supply to the fruit through the xylem. However, no consistent effect of the ECS and shading on the Ca concentration in fruit was found.

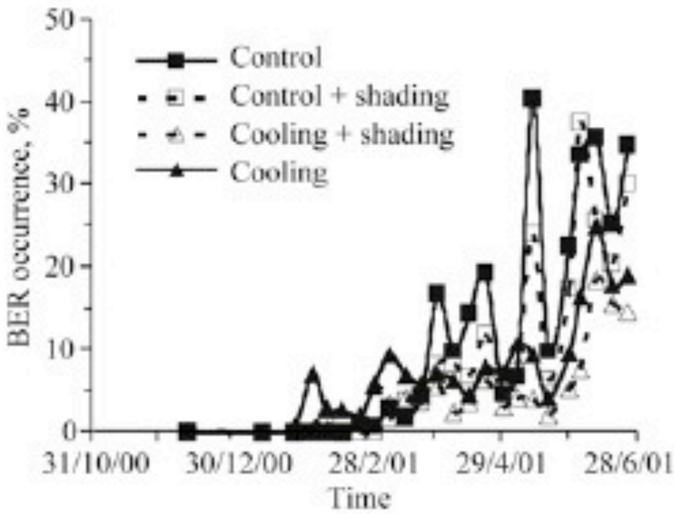

Fig. 4. Effect of evaporative cooling system and shading on the occurrence of BER in pepper fruits.

The use of the ECS reduced the incidence of BER-affected pepper fruits (Bar-Tal et al. 2006; Turhan et al., 2006b). Bar-Tal et al. (2006) reported that the air temperature and the incidence of BER increased with the distance from the wet pad, and high positive correlations were found between the incidence of BER and the average air temperature at midday during the spring. In 3 years of experiments Bar-Tal et al (2006) found no clear and consistent effect of the ECS on the Ca concentration in the fruit. Thus, the incidence of BER-affected fruits did not correlate with the Ca concentration in the fruits.

Irrigation frequency and Ca concentration in the solution

The incidence of BER in tomato has been reported to be influenced by the irrigation regime and the quantity of irrigation water (Bangeth, 1979). Bar-Tal et al (2001d) reported that the lowest BER incidence was obtained when the most frequent irrigation was combined with the highest solution Ca concentration (Table 1). High irrigation frequency enhanced the Ca concentration in the leaves and fruits, especially in the low-Ca treatment (Table 2), and minimized the amplitude of the fluctuations in the water content of the growth medium, and these effects of the high irrigation frequency probably enhanced the Ca uptake and reduced the BER. In an additional experiment we found that increasing the irrigation frequency in soilless culture from 1 to 12 times a day reduced the percentage of BER-affected pepper fruits from 35 to 25% (Turhan et al., 2006b). Silber et al. (2005) reported that increasing the fertigation frequency from two to eight and to 30 applications per day reduced the number of BER-affected fruits from 7 to 3 and to 2 per plant, respectively, and increased the yield of export-quality fruits from 6.5 to 10 and to 10.5 per plant, respectively.

The Ca concept

Although the Ca supply to the fruit is considered to be an important factor in the occurrence of BER, many attempts to define critical values or even to correlate BER incidence with the Ca concentration or the K/Ca ratio in tomato and pepper fruits have failed (Chiu and Bould, 1976; Nonami et al., 1995; Saure, 2001; Bar-Tal et al., 2006). Possible reasons are: i. the fruit is susceptible to the Ca concentration and the K/Ca ratio only during a very short period in early fruit development (Ehert and Ho, 1986b; Ho, 1989; Marti and Mills, 1991; Ho et al., 1993; Marcelis and Ho, 1999); and ii. The Ca concentration in the fruit is very low and varies with the distance between the distal part and the blossom end (Ehret and Ho, 1986b; Ho et al., 1987; Marcelis and Ho, 1999). The critical Ca concentration for the induction of BER may vary with environmental conditions that affect the fruit growth rate (Ho et al., 1993; Marcelis and Ho, 1999). According to Ho and White (2005) BER occurs during a period of high cellular Ca demand, when fruit growth is accelerated or Ca delivery to the fruit is limited; it is initiated by a cellular dysfunction in a fruit cell during expansion, in response to a local, transient Ca-deficiency. During cell expansion, there is a considerable demand for Ca^{2+} as a structural component of new cell walls and membranes, and as a cytosolic signal in the form of a counter-cation in the enlarging vacuole, which orchestrates the allometry and biochemistry of cell expansion. The specific stage of fruit development is crucial, since the Ca concentration in the fruit decreases during fruit growth and ripening (Marcelis and Ho, 1999; Bar-Tal et al., 2001b; Ho and White, 2005; Bar-Tal et al., 2006; Turhan et al., 2006b). Better correlation of the BER incidence with Ca concentration was obtained when analyses of fruit sections were used (Bar-Tal et al., 2001b). However, Nonami et al. (1995) failed to establish a correlation between BER incidence and Ca concentration in tomato fruits that were divided into several sections. Saure (2001) concluded that stress rather than Ca supply was the main causative factor of BER.

Oxidative stress

However, these stress factors have been neither explored nor identified. Aktas et al. (2005) suggested that oxidative stress contributes to BER initiation in bell pepper grown under stress; they reported that BER symptoms were highly enhanced in plants grown in saline conditions during the spring and summer. The fruit calcium concentration was not affected by salinity, but manganese concentrations in both leaves and fruits were significantly reduced under these conditions (Aktas et al. 2005). Under salinity reactive oxygen species (ROS) production in the apoplast was enhanced, partly as a result of increased NAD(P)H oxidase activity in the pericarp of pepper fruit at the stage in which it was most sensitive to BER (Aktas et al., 2005). Apoplast ROS production and extracted NAD(P)H oxidase activity were inhibited by manganese, zinc and, to a lesser extent, calcium. These cations, especially manganese, also negated the enhancement of ROS production that occurred when fruit pericarp discs were incubated in NaCl solutions (Fig. 5). Manganese, zinc and calcium, when infiltrated into fruit pericarp discs, also inhibited NAD(P)H oxidase activity in extracts. These results suggest that generation and scavenging of oxygen- free radicals in the apoplast may contribute to the appearance of BER symptoms in pepper fruits under saline conditions (Aktas et al., 2005). Turhan et al. (2006) reported that apoplast-associated peroxidase activity, ascorbic acid, SOD and H_2O_2 may play important roles in controlling salinity-related damage to pepper fruit.

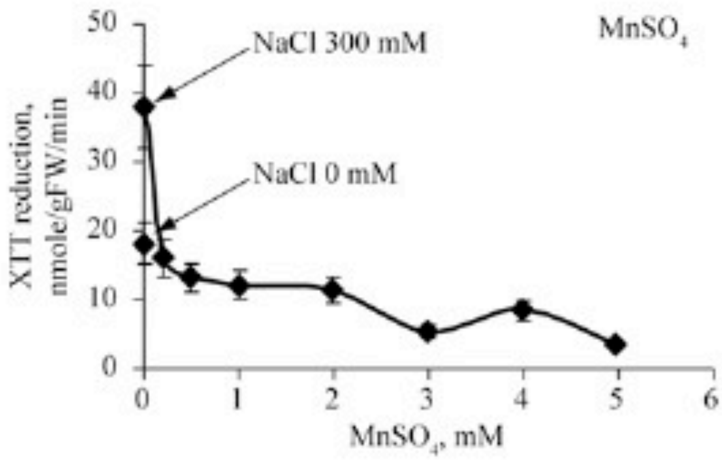

Fig. 5. The effects of Mn on the NaCl-induced enhancement of the XTT reduction rate by fruit pericarp discs (after Aktas et al., 2005).

XTT – {2,3-bis(2-methoxy-4-nitro-5-sulfophenyl)-5-[(phenylamino) carbonyl]-2H-tetrazolium hydroxide}.

Does Mn play role in BER occurrence?

Silber et al. (2005) reported that Mn concentrations in pepper fruits under low-frequency fertigation were low, probably in the deficiency range, but that they increased with increasing fertigation frequency. During the course of the experiment a negative correlation was found between the accumulated number of BER-affected fruits and the fruit-Mn concentrations (Silber et al., 2005). In light of these findings and of the data on the effect of salinity on the incidence of BER-affected fruits (Fig. 3) and on Mn concentration in the fruits (Table 4) we conducted an experiment to investigate the possible effect of Mn concentration on BER incidence in pepper fruits. We found that elevating the Mn concentration in the solution from 0.15 to 1.0 mmol/L dramatically reduced the percentage of BER-affected pepper fruits during the summer (Fig. 6).

Conclusions

BER is a physiological disorder that is influenced strongly by fertigation management and environmental conditions. BER occurrence has been related to reduced translocation of calcium to the fruit tip under stress conditions, and it is, therefore, referred to as a "calcium-related disorder". In light of recent findings that BER effects in the fruit tissue include the production of oxygen free-radicals and diminution of anti-oxidative compounds and enzymatic activities (Aktas et al. 2005; Turhan et al. 2006a), and the known crucial role of manganese in enzyme activities and in detoxification of oxygen free-radicals, the relationships between BER incidence and fruit-Mn concentration may indicate that BER is also related to Mn deficiency.

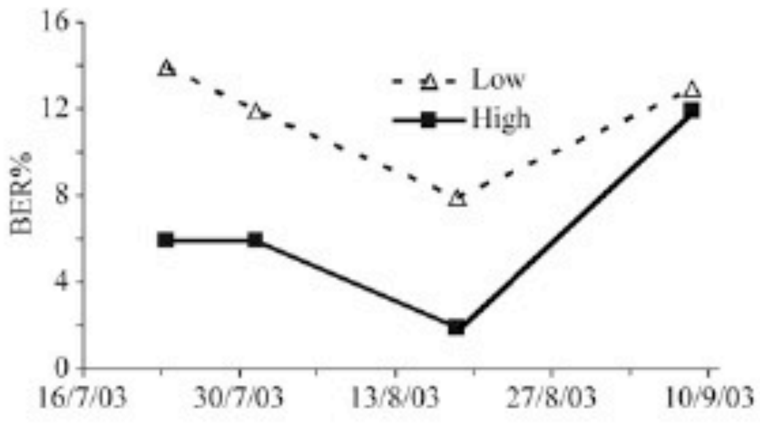

Fig. 6. Effect of Mn concentration in the irrigation water on BER incidence in pepper fruits.

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Fertigation in Micro-irrigated Horticultural Crops: Vegetables

Salvadore J. Locascio

Horticultural Sciences Department, University of Florida, Gainesville, FL 32611-0690, USA. E-mail: sjl@ifas.ufl.edu.

Abstract

Fertigation is the injection of soluble nutrients into irrigation water to enhance crop production. In combination with micro-irrigation (drip irrigation), this technique forms an efficient method for precisely applying nutrients close to the crop root zone, especially when a polyethylene mulch is used. Vegetables are grown throughout the world on a wide variety of soil types and in various climates; China is the leading vegetable producer, followed by India and the United States. In most areas were vegetables are grown, mineral nutrients and irrigation must be provided to reduce nutrient and moisture stress and to maximize production. Where water is expensive or in short supply, drip irrigation is replacing surface and sprinkler irrigation; it is generally used in combination with polyethylene mulch on high-value crops, including tomato (Lycopersicon esculentum), pepper (Capsicum annuum), eggplant (Solanum melongena), strawberry (Fragaria × ananassa) , and cucurbits. Because soluble nutrients move with the wetting front, precise management of irrigation quantity, and rate and timing of N and K application are critical for efficient vegetable production. Drip irrigation can be scheduled to match the water evaporation from the crop or by use of such instruments as tensiometers. It is essential to avoid excessive irrigation and, on coarse textured soils, to apply only 30 to 40% of the N and K required for the crop at planting, with the remainder60 to 70% applied by fertigation. Generally other needed nutrients, including P, Mg, Ca, and micro-nutrients, are most efficiently applied preplant, in dry formulations and not by fertigation. For many vegetables, fertigation of N and K can be applied bi-weekly, weekly or daily. Drip fertigation systems are generally costly and require more management than seepage or sprinkler irrigation systems. With drip irrigation, water use is reduced, nutrient application is precise, diseases are reduced because the foliage remains dry, and yields of some corps are increased. With fertigation, nutrient use efficiency is increased and the risk of loss of nutrients to the ground water is reduced. Information from studies to support this production system is presented.

Keywords: drip irrigation, irrigation schedule, polyethylene mulch, nutrient source, nutrient application timing.

Introduction

Fertigation is the application of soluble nutrients with via the irrigation water; its use in vegetable production has increased with the introduction of polyethylene mulch and drip irrigation, and it is an efficient means to apply fertilizer to the root zone. For efficient use of fertigation, water application and nutrient application must be precisely managed, to prevent over-watering and nutrient leaching. A wide variety of vegetables are grown throughout the world, on many soil types and in various climates. Soils commonly used to produce vegetables range from coarse-textured sands with water-holding capacity of 8 to 15% to fine-textured silt and clay soils with water holding capacities of over 40%. Soil textures vary from rocky and gravely to the widely used organic soils. Production areas range from humid with high rainfall to very dry or arid with little or no rainfall. In most areas where vegetables are grown successfully, irrigation is essential to supplement irregular rainfall, to minimize plant water stress (Doss, et. al., 1980; Locascio and Myers, 1974), and one or more mineral nutrients must be applied to maximize crop production (Hartz and Hochmuth, 1996). Highly inefficient surface irrigation is most commonly used worldwide, wherever water is abundant and inexpensive. Surface systems are inexpensive to install and easy to manage, but their water-use efficiency is lower (33%) than that of drip irrigation. Overhead sprinklers were introduced in the 1940's and are still used extensively on vegetables. The water flows to the field through conduits and is applied through overhead nozzles. These systems are more efficient (about 75% in the absence of mulch) and apply water more uniformly than surface irrigation, and can be used on uneven fields. However, they are more costly than surface irrigation systems, and are more complex to manage. In the 1950s, polyethylene mulch was introduced (Lamont, 2005) and its use drastically changed vegetable fertilization practices. With the so-called plasticulture, nutrient leaching is reduced, soil temperatures can be increased by the use of black mulch, most weeds are controlled, and yields are generally increased. Polyethylene mulch is now widely used on many vegetable crops worldwide. China leads the world in the use of polyethylene mulch for vegetables and in vegetable production, followed in vegetable output by India and the United States (Economic Research Service, USDA, 2005). In the 1960s, micro-irrigation (drip irrigation) systems were developed (Hall, 1971), and they are slowly replacing the more commonly used surface and overhead sprinkler systems in areas where the water supply is limited. However, drip systems are more costly and require a higher degree of maintenance and management than

other irrigation systems. These highly efficient (about 90 to 95%) drip irrigation systems apply small amounts of water on a daily basis, through outlets (emitters) in low-pressure hoses placed close to the crop. Advantages of drip irrigation over other systems include: reduction of water use by over 50%; drier crops and row middles, which results in better insect and disease control; reduced weed growth in row middles; drier harvesting conditions; use of smaller pumps to provide small amounts of water daily, in contrast to large amounts applied on a 5- to 7-day schedule; and, very importantly, the ability to precisely control the application of plant nutrients (i.e., fertigation) and certain pesticides with the irrigation water (Locascio, 2005). Fertigation systems can be used without mulch, similarly to all irrigation systems, but are most efficiently used with drip-irrigated, higher-valued polyethylene mulched vegetables, in areas were water availability is limited. The timing of irrigation and nutrient application for polyethylene mulched, drip irrigated vegetables are discussed below.

Watering schedule with drip irrigation

To minimize leaching of the soluble nutrients used with drip irrigation, and to maximize crop production, precise management of water application is essential, since over-irrigation results in nutrient leaching and reduced yields (Bar-Yosef, 1977). Even with fertigation, over-irrigation can result in severe nutrient deficiencies and reduced crop yields, e.g., excessive drip irrigation reduced tomato yield (Locascio et al., 1989). Drip irrigation can be scheduled by matching a predetermined proportion of the water evaporated from a U. S. Weather Service Class A evaporation pan (E pan) (Phene et al., 1973; Smajstrla et al., 2000), which provides a measure of evapotranspiration (ET). Yields of polyethylene-mulched tomato were lower with drip irrigation at 2.0 E pan than at 1.0 E pan (Locascio et al., 1981). On a coarse-textured soil yields of a spring tomato crop were higher when irrigated at 0.5 E pan than at 1.0 E pan (Locascio et al., 1989), and the maximum yield was produced above 0.5 E pan, at about 0.75 E pan (Locascio and Smajstrla, 1989), whereas on a fine-textured soil, tomato yields were similar under irrigation at 0.5 and 1.0 E pan (Locascio et al., 1989; Olson and Rhoads, 1992) with water application of 20 to 30 cm/ha, similar yields were obtained with one and with three irrigation applications per day on both soils. Pitts and Clark (1991) found that tomato water requirements varied from 0.2 E pan early in the season to 0.8 E pan during fruit development. Water scheduling according to pan evaporation often over-estimates early crop water needs: when tensiometer scheduling of water at 10 to 15 kPa was used, less water was applied than with 0.75 E pan application. On tomato, water used per crop was 30 cm with water scheduled to replace 0.75 E pan and 17 cm when irrigation was scheduled by means of magnetic switching tensiometers to apply sufficient water to maintain soils at 10 kPa (Locascio and Smajstrla, 1996; Smajstrla and Locascio, 1996). On finer-textured soils, sufficient water is applied to maintain the soil at 20 to 50 kPa (Locascio et al., 1992). In addition to tensiometers, soil water sensors and techniques that can be used to determine the time of irrigation include granular matrix sensors (GMSs) (Eldredge et al., 1993) and time-domain reflectometry (TDR) (Topp et al., 1984).

Soluble dyes can be applied with the irrigation water to track the depth of water and soluble-nutrient movement (Eger et al., 2001; Simonne et al., 2003). Excessive irrigation moves nutrients below the root zone and should be avoided.

Nutrient requirements

The use of fertigation generally does not change the fertilizer requirements of a particular crop. Total fertilizer nutrient requirements vary with location, soil type, and crop (Hartz and Hochmuth, 1996). Most soils, except for organic soils, are deficient in N, which must be applied for most annual vegetables. Most mineral soils also lack P and K, which are applied to each crop. Needs for secondary and micro-nutrients vary widely according to the crop and the fertility of the soil, and the needs for P, K, secondary nutrients, and some micro-nutrients should be established by means of calibrated soil tests. Growers should use fertilizer recommendations developed by local scientists on the basis of soil fertility and crop needs, as exemplified by vegetables grown in Florida (Hochmuth and Hanlon, 1995).

The use of plasticulture often enables a double crop or a second crop to be grown after the initial crop. With drip irrigation, fertigation facilitates the application of nutrients for this second crop. Proper management of the first crop leaves little residual N and K for the second crop, which, therefore, should be fertigated with nutrients as required for a first crop (Clough et al., 1987). Soil tests should be used to determine the P and K requirements. Micro-nutrients applied for the first crop are generally sufficient for a double crop.

Fertigated nutrients

All soluble nutrients can be applied effectively by fertigation with drip irrigation, but N and K are the main nutrients applied in this way, because they move readily with the irrigation water. All other needed nutrients generally can be applied most efficiently preplant. Fertigation P and most micro-nutrients move very poorly in the soil and do not reach the root zone. Needed P, secondary elements, and micro-nutrients are most efficiently applied preplant in the root zone. Use of fertigation to apply P and micro-nutrients together with Ca and Mg may cause precipitation and blockage of the emitters (Imas, 1999), and therefore should be minimized. When conditions require that P be applied by fertigation, it should be applied alone and the irrigation water should be acidified, to prevent clogging of the emitters (Rolston et al., 1981). Were micro-nutrient deficiencies occur and applications are made via fetigation, completely soluble sources or chelates can be used.

Scheduling of N and K fertigation

The scheduling of nutrient application with drip irrigation is critical to the efficient use of nutrients, especially on coarse-textured soils, and requires some change in the way fertilizer is applied. When all nutrients were applied preplant in the bed, as with overhead- and surface-irrigated, polyethylene-mulched crops, both sprinkler and drip irrigation resulted in similar yields of tomato (Doss et al., 1980; Locascio and Myers, 1974) and of watermelon (Citrullus lanatus) (Elmstrom et al., 1981). When part of the N and K was applied preplant and part by fertigation with drip irrigation, yields were higher than with overhead irrigation for tomato (Locascio and Myers, 1974), muskmelon (Cucumis melo) (Shmueli and Goldberg, 1971), and strawberry (Locascio and Myers, 1975). With 100% preplant application of N and K, tomato yields were lower than when 50% was applied by fertigation (Dangler and Locascio, 1990). On a coarse-textured soil preplant application of all the P and of 40% of the N and K, with 60% of the N and K fertigated with drip irrigation tomato yields were greater than when all nutrients were applied preplant (Locascio and Smajstrla, 1989; Locascio et al., 1997b).

With drip irrigation on a coarse-textured soil, it is essential to supply only part of the N–K requirement via fertigation and to avoid over-irrigation. With part of the nutrients applied at planting, nutrient leaching is reduced, nutrient use efficiency is increased, and this generally results in higher yields than if all the nutrients were applied either preplant or through the drip system (Locascio et al., 1997b). In a 2-year study on fine-textured soils, however, yields were higher when 100% of the nutrients were applied before planting than when all or part of them were applied by fertigation (Locascio et al., 1997b). Split applications of nutrients were reported to maximize production of pepper (Hartz et al., 1993) and muskmelon (Bogle and Hartz, 1986). Preplant incorporation of N and K in the root zone provides nutrients for early growth during a period when irrigation may not be required, and before fertigation begins to supply nutrients throughout the bed as crop growth continues.

Frequency of fertigation

Fertigation can be applied with each irrigation or on a scheduled basis to prevent nutrient stress. Since nutrient uptake increases with plant growth, some schedules ensure that the fertigation rate increases according to the crop growth curve. However, Locascio et al. (1997b) Locascio and Smajstrla (1989) found that with 40% preplant N and K application, similar yields were obtained with six 2-weekly or 12 weekly applications, either all equal or scheduled with initially small amounts that increased progressively with plant growth, and with daily or weekly fertigation. The frequency of fertigation – daily, weekly or 2-weekly – and whether the applications were uniform or increased progressively to match the plant growth were not critical, so that fertigation can be planned to suit the equipment available and the grower's convenience. Application of 100% of the N and K either preplant or by fertigation resulted in lower production than the split application (Locascio et al., 1989). On finer-textured soils, response to fertigation was not as consistent as on coarse ones, although N, and sometimes K, are most usually applied through fertigation to increase nutrient use efficiency. With subsurface drip-irrigation, broccoli (Brassica oleracea var. italica) yields were similar with fertigation at 1, 7, 14 and 28-day intervals (Thompson et al., 2003). It is apparent that to maximize crop yield on coarse-textured soils, 30 to 40% of the N and K must be applied preplant and the remainder by fertigation and that the actual schedule for fertigation is not critical.

Fertigated N and K sources

All soluble nutrient sources are suitable for fertigation, and selection is generally according to the cost and the other element in the salt. Sources of N that perform similarly to one another in the fertigation of vegetables include ammonium nitrate, calcium nitrate, ammonium sulfate and potassium nitrate (Hartz and Hochmuth, 1996; Locascio et al., 1982; Locascio et al., 1984, Locascio and Martin, 1985). Also, urea can be applied via fertigation, but, studies have shown that nitrification of urea may be slow in fumigated soils (Fiskell and Locascio, 1983), and that some nitrate-N should be applied after soil fumigation, especially in cooler soils. Suitable K sources for fertigation include potassium chloride, potassium sulfate, and potassium nitrate, which generally perform very similarly to one another (Locascio et al., 1997a). Growers' concerns about the use of the chloride source are generally unfounded, except where saline water is used, where the soil is saline, or when application rates are excessive. On soils low in organic matter, S deficiencies may occur if some S-containing fertilizer is not applied either before planting or through fertigation; the required S can be supplied by applying part of the fertigated N or K in the form of S-containing fertilizers such as ammonium sulfate, ammonium thiosulfate, or potassium sulfate. On a low-S soil cabbage yields were higher when S was applied by fertigation than when applied preplant (Susila and Locascio, 2001); this indicates the importance of S fertigatiom on coarse-textured soils.

Drip fertigation system components

Drip irrigation systems are complex and include pumps, backflow-prevention systems, filters, nutrient storage tanks, fertigation injectors, timers, and drip tubing. Clogging of emitters is a major concern, and efficient management and maintenance of the system are necessary (Imas, 1999). Drip irrigation and fertigation can be applied with smaller pumps than those used with other irrigation systems, since only a small amount of water is applied on a daily basis, which reduces pumping costs (Prevatt et al., 1992). Because of the complexity of the numerous system components, drip/fertigation systems are more costly ($1,200/ha) than subirrigation system ($470/ha), therefore, drip/fertigation systems are used mostly in areas where water is scarce and costly, and on relatively high-value crops.

Fertigation is an efficient method to apply part of the fertilizer in a precise manner during the crop growing season. The nutrients most commonly applied in this way are N and K. Other nutrients are more efficiently applied preplant, in dry formulations. Efficient use of fertigation enables precise nutrient application, reduces the likelihood of nutrient leaching, and increases crop production.

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Yield and Fruit Quality of Tomato as Affected by Rates and Ratios of K and Ca in Water Culture System

B. Nzanza, Diana Marais, and Andries S. Claassens

Department of Plant Production and Soil Science, University of Pretoria, 0002 Pretoria, South Africa. E-mail: andries.claassens@up.ac.za.

Abstract

A water culture experiment in a greenhouse investigated the effects of K:Ca ratios and rates on yield and quality of tomato. A factorial experiment included two levels of K (6 and 10 $mmol_c/l$), two levels of Ca (12 and 16 $mmol_c/l$) and four K:Ca $mmol_c/l$ ratios (6:12, 6:16, 10:12, 10:16). Treatments were replicated four times in a fully randomized design with tomato cv. “Money Maker” as the test crop. The total marketable yield of tomato decreased, mainly because of a high incidence of physiological disorders, including small fruits. High K rates in the nutrient solution decreased fruit pH, and increased titratable acidity (TA) and total soluble solid (TSS). High Ca (16) rates combined with low K (6) decreased the K content of tomato fruits. Low K in the nutrient solution increased the incidence of blotchy ripening (BR), whereas low Ca increased the incidence of blossom end rot (BER). There was no evidence that these plant nutrients influenced the occurrence of fruit cracking (FC) or cat facing (CF).

Keywords: calcium, fruit quality, potassium, tomato, yield, water culture.

Introduction

Fruit quality is a crucial factor in the production of greenhouse tomatoes, and it is strongly influenced by K. Potassium plays a key role in charge balance and certain metabolic and transport processes, as well as turgor regulation (Dorais et al., 2001); it influences fruit shape, reduces ripening disorders, and enhances acid concentration (Adams et al., 1978). With adequate K nutrition, the fruit is generally higher in total solids, sugars, acids, carotene, and lycopene, and has a better keeping quality (Munson, 1985).

Potassium accumulates to a greater extent than other nutrient elements, which leads to considerable demands for this mineral (Williams and Kafkaffi, 1998; Voogt and Sonneveld, 1997). A main cause for concern in elevating K in the nutrient solution is its antagonistic effect on the uptake of other nutrients, such as Ca, N, or Mg. A high K:Ca ratio has been reported to increase BER (Bar Tal and Pressman, 1996).

The aim of this experiment was to investigate the effects of K and Ca rates and ratios on yield and quality of tomato under certain South African conditions.

Materials and methods

A greenhouse experiment was conducted at the experimental farm of the University of Pretoria. The factorial experimental design included two levels of K (6 and 10 $mmol_c/l$), two levels of Ca (12 and 16 $mmol_c/l$) and four K:Ca $mmol_c/l$ ratios (6:12, 6:16, 10:12, 10:16); there were four replications. Tomato cv. "Money Maker" seedlings were transplanted into 10-l pots on a rotating table. The main stems were trained and allowed to grow to five trusses. Lateral shoots were removed but fruit was not thinned. Treatment combinations were prepared by modifying a Hoagland no. 2 solution. The nutrient solutions were monitored regularly for pH and EC, and replaced fortnightly. At harvest, fruits were collected to determine yield and quality factors, such as physiological disorders, size, pH, TSS, TA, EC, dry matter. Leaf and fruit samples were chemically analysed for K, Mg, Ca, N, and P. Analysis of variance (ANOVA) was applied to each parameter at $P < 0.05$. In case of significance Turkey's LSD test was applied.

Results

Table 1 presents the response of tomato to K: Ca ratios, as expressed in fruit disorders and effects on marketable yields. There were no significant differences in marketable yields, though the treatment supplied with high K and Ca (10:16) showed the highest marketable yield, and the low K and Ca (6:12) treatment the lowest. High Ca (16) reduced the incidence of BER. Blotchy ripening occurred only in low-K treatments. FC and CF were not affected by treatments.

Table 2 summarizes the effects of K:Ca ratios on tomato fruit quality. Fruit pH and EC were significantly higher at low K:Ca ratios. Titratable acidity, TSS, and fruit dry matter (DM) were not significantly affected by rates and ratios of K and Ca in the nutrient solution.

Table 1. Effects of K:Ca ratios on fruit disorders (g/fruit) and marketable yield of tomato.

K:Ca ratio	BER	BR	FC	CF	Small fruit	Marketable yield
	------------------------------------ % ------------------------------------					
6:12	2.75 a	0.42 a	2.14 a	0.89 a	3.19 a	90.62 a
6:16	0.93 b	0.96 a	2.20 a	0.91 a	3.23 a	91.77 a
10:12	2.32 a	0b	2.18 a	0.53 a	3.35 a	91.62 a
10:16	0.41 b	0b	2.59 a	0.40 a	3.28 a	93.32 a

Means followed by the same letter in a column are not significantly different according to Turkey's test at P <0.05.

Table 2. Effects of K:Ca ratios on tomato fruit quality.

K:Ca ratio	pH	TA	TSS	EC	DM
		nmol/L	%	dS/m	%
6:16	4.1875 a	67.50 a	4.92 a	4.765 ab	5.355 a
6:12	4.1625 a	66.75 a	4.902 a	4.6875 b	5.5725 a
10:16	4.075 b	72.25 a	5.075 a	4.8275 a	5.4025 a
10:12	4.0775 b	71.75 a	5.0675 a	4.7875 ab	5.59 a
LSD	0.038	4.28	0.1409		0.2625
CV	0.751	5.648	2.593	1.701	0.262

Means followed by the same letter in a column are not significantly different according to Tukey's test at P <0.05.

The effects of K:Ca ratios on the mineral contents of fruit are presented in Table 3. The data revealed no significant differences among treatments, in the mean contents of N, Ca, and Mg the fruit, whereas the P and K contents were highest at a K:Ca ratio of 6:12 and lowest at a ratio of 6:16.

Table 3. Effects of K:Ca ratios on mineral contents of tomato fruits.

K:Ca ratio	N	P	Ca	K	Mg
	------------------------------------	--------- %	----------------	-------------------	----------------
6:16	2.125 a	0.35 b	0.14 a	2.995 b	0.115 a
6:12	2.425 a	0.475 a	0.147 a5	3.575 a	0.1225 a
10:16	2.25 a	0.4 ab	0.1325 a	3.145 ab	0.1175 a
10:12	2.525 a	0.425 ab	0.18 a	3.4425 ab	0.1225 a
LSD	0.40009	0.0943	0.06092	0.5003	0.0162
CV	11.161	14.875	26.352	9.948	8.802

Means followed by the same letter in a column are not significantly different according to Turkey's test at $P < 0.05$.

Discussion

The results showed that tomato yield was most affected by physiological disorders such as BER. BR was observed only in low-K treatments, which indicates that K deficiency plays a key role on the incidence of this disorder. No relationship has been found for FC and CF that affected the marketable yield (Table 1). This study showed the beneficial effect of elevated K levels in improving fruit quality. High K rates increased TA, TSS and EC, and decreased fruit pH. High Ca combined with low K decreased the percentage of K in the fruit (Table 3). Based on these findings it seems clear that proper K nutrition improves fruit quality of tomato.

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Do Algae Cause Growth-Promoting Effects on Vegetables Grown Hydroponically?

Dietmar Schwarz, and Lothar Krienitz

Institute for Vegetable and Ornamental Crops, Theodor Echtermeyer Weg 1, D-14979 Grossbeeren, Germany. E-mail: Schwarz@igzev.de.

Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Alte Fischerhütte 2, D-16775 Stechlin, Germany.

Abstract

Fertigation systems, especially hydroponic systems with recirculating nutrient solution, are an ideal environment for algal growth, but it is not clear if this contaminant affects the crop. Therefore, greenhouse experiments were carried out to monitor the development and composition of algae, as well as their effects on lettuce and cucumber performance. In addition, several different substrates and water sources, with differing algal communities, were tested for their effects of on both algae growth and crop performance. In open troughs, algal density was lg 4.2 to 4.6 cells/ml in the lettuce and lg 3.7 to 4.6 cells/ml in the cucumber experiment. Algal density and composition were mainly influenced by initial density in the different water sources. Moreover, plant species, temperature, and concentration of the nutrient solution also affected the density. The diversity of the algal community was poor; only unicellular species were observed with Chlamydomonas spp. and Pseudodictyosphaerium spp. as main representatives in the drain water. Cucumber and lettuce shoot fresh weight, and therefore lettuce yield, were reduced significantly in the presence of algae, but cucumber yield was not affected. Overall, the present results indicate that the effects of algae depend on several factors, and therefore do not enable generalization on whether algae have a negative or positive impact on crop growth in hydroponic systems.

Keywords: fertigation, clogging, recirculation.

Introduction

Algae often thrive in fertigation systems, particularly when there is sufficient light, and they can cause problems with the water supply system by clogging drippers or drip lines (Ravina et al., 1997). In addition, algae compete for nutrients, and certain species are known to produce toxins that might inhibit or even stop crop growth (Huizebos et al., 1993; Borowitzka, 1995). Therefore, one common means to prevent, or at least reduce, algal growth is to cover the root system with black plastic sheets. Alternatively, algaecides are used occasionally (Vänninnen and Koskula, 1998; Nonomura et al., 2001). These precautions cause additional costs for the farmer, and also produce pollutants.

However, algae may also be beneficial for plant growth. The oxygen produced by algal photosynthesis prevents anaerobiosis in the root system of the crop. Furthermore, algae recently have been reported to release plant-growth promoters in plant cultivation systems (Mazur et al., 2001). Among these plant-growth regulators are auxins, cytokinins, gibberellins, abscisic acid, and ethylene (Van Staden, 1999). Other growth-promoting effects may be more indirect, e.g., enhancing the water-holding capacity of soils or substrates, improving the availability of plant nutrients (Möller and Smith, 1998), or producing antifungal and antibacterial compounds (Cannell, 1993; Borowitzka, 1995). Very little is known about the positive or negative effects of algae that occur naturally in fertigation systems, although several green algae, such as Scenedesmus spp. and Chlorella spp. were reported to excrete plant growth-promoting substances (Ördög, 1999; Mazur et al., 2001).

Therefore, two experiments were carried out to answer the following questions:

Is the cultivation of algae in fertigation systems, such as hydroponics, possible?

Does the water source affect the algal density and composition in the cultivation systems?

Do the characteristics of the plants and substrates affect algal development during cultivation?

Does the algal community influence plant growth?

Material and methods

Water sources and characterization of algae

Water from several different sources at or close to Grossbeeren (Germany, lat. 52°N; long. 13°E) was used for mixing the nutrient solutions in our experiments. The sources were: a) a rainwater pond, b) a peat ditch, and c) osmotic water.

The nutrient solution contained: as macro-nutrients (mM), NH_4NO_3 (1), $Ca(NO_3)_2 \cdot 4H_2O$ (4.5), KNO_3 (7.5), KH_2PO_4 (2), K_2SO_4 (1), $Mg(NO_3)_2$ (1); and as micro-nutrients (µM), FeEDTA (40), $MnSO_4$ (5), H_3BO_4 (30), MoO_3 (0.5) $CuSO_4$ (0.75), $ZnSO_4$ (4) (De Kreij et al., 1999). The algal density and composition were characterized in all water sources before the experiments and in the nutrient solutions frequently during the experiments. The samples were examined under a light microscope. Species were quantified by means of a NEUBAUER counting chamber and their populations expressed as cells per millilitre.

Greenhouse experimental setup

Head lettuce (Lactuca sativa var. capitata cv. Charlen) plants aged 20 days were transferred to a 200-m^2 greenhouse, where they grew in 20 troughs measuring 8.0 × 0.2 × 0.07 m from March 5 to April 11, 2002. Each trough contained 37 lettuce plants. Six treatments were applied, in a twofold cross classified design, with trough cover and hydroponic system as treatment factors, in three replications. Half of the troughs were covered with a black/white plastic sheet to prevent algal growth (A-) and the other half were not (A+). The second treatment factor was the substrate used: vermiculite, a polyester fleece, and no substrate (Nutrient Film Technique). Black polyester fleece (80 $g \cdot m^{-2}$) covered the bottoms of the troughs, which were filled to the brim with vermiculite. The first treatment was chosen to investigate the algal density and its influence on lettuce growth. The second treatment was chosen to check whether the growth medium and hence, the conditions in the root environment affect algal density and population composition. Nutrient solution was supplied intermittently, depending on the radiation level, for 45 s every 2 to 15 min, at 2 l per trough. The solution was supplied via TSX-510-15-1000 drip lines (Tee Jet) put on the substrate surface. The solution EC was set to 2.5 dS/m and pH to 6.0.

Cucumber (Cucumis sativus cv. Corona) plants aged 20 days were transferred to a 200 m^2 greenhouse, where they grew in 18 troughs measuring 8 × 0.2 × 0.07 m from 10 March to 11 April 2005. Each trough contained 11 cucumber plants. Six treatments were applied, in a twofold cross classified design, with trough cover and water source as treatment factors, in three replications. Half of the troughs were covered with a black/white plastic sheet to prevent algal growth (A-) and the other half with a transparent plastic sheet (A+). The second treatment factor was the water source, as mentioned above. The first treatment factor was chosen to investigate the algal population and its influence on cucumber growth. The second treatment was chosen to check whether the water source affected algal density and population composition, and hence, plant growth and yield. Nutrient solution was supplied continuously at about 2 L/min via drip lines with a dripper for each plant, by means of a Nutrient Film Technique. The solution EC was set to 3.0 dS/m and pH to 6.0.

Greenhouse temperature controls were set to heat if temperatures dropped below 15/12°C (day/night) for lettuce and below 22/19°C for cucumber. Ventilation was started if the temperatures exceeded 18 and 28°C, respectively. Humidity and CO_2 concentration were ambient and not controlled. The micro-climates in the greenhouse, the EC and pH in the drains from the troughs, and the temperatures in the root environments were monitored.

Yield, shoots, and roots were harvested and fresh and dry weighed. Fresh samples were taken from the root system (50 mm from the rock-wool cube) to measure specific root length (Tennant, 1975) and mean root diameter. Total root length per plant was calculated as the product of specific root length and total root dry weight.

Results and discussion

Population dynamics of algae

The algal density was about 9,000 cells/ml in rain water and at the start of the experiments. It was lower in the other water sources and zero in the osmotic water. After water was supplied to the troughs covered with the black/white foil the algal density decreased continuously in both experiments until 2-3 weeks after the start, when no cells were found by microscopic examination. In contrast, in the open troughs and in those covered with a transparent foil the algal density increased to a maximum of about 35,000 cells/ml and remained fairly constant at this level in the lettuce experiment (Fig. 1). In the cucumber experiment algal density remained at this level only when rainwater was used. The density in the cucumber troughs supplied from the other water sources was about half of the above figure, and it diminished to 7,000 cells/ml at the end of the experiment. Density was affected by the substrates and by the water sources (Fig. 2A, B). Overall, the algal density was highest on vermiculite and least on the fleece, with intermediate density where there was no substrate. In the cucumber experiment the highest density was observed in the rainwater, followed by water from the peat ditch, and was least in the osmotic water. Cultivation of algae was simple although it was not found possible to maintain a constant density or a specific composition. This difficulty was attributed to likely variations in micro-climate and nutrition, such as substrate temperature and nutrient solution EC. Climatic and nutritional effects on algal density in water from natural sources were reported by Sunda and Huntsman (1998) and Wetzel (2001), and this might also account for the decrease in algae density in the drain solution at the end of the present cucumber experiment. Although the filamentous Ulothrix spp. could have caused filter clogging (Juanica et al., 1995; Ravina et al., 1997), we did not observe any problems, most likely because of the low temperature in the lettuce experiment and the relatively short cultivation period in the cucumber experiment.

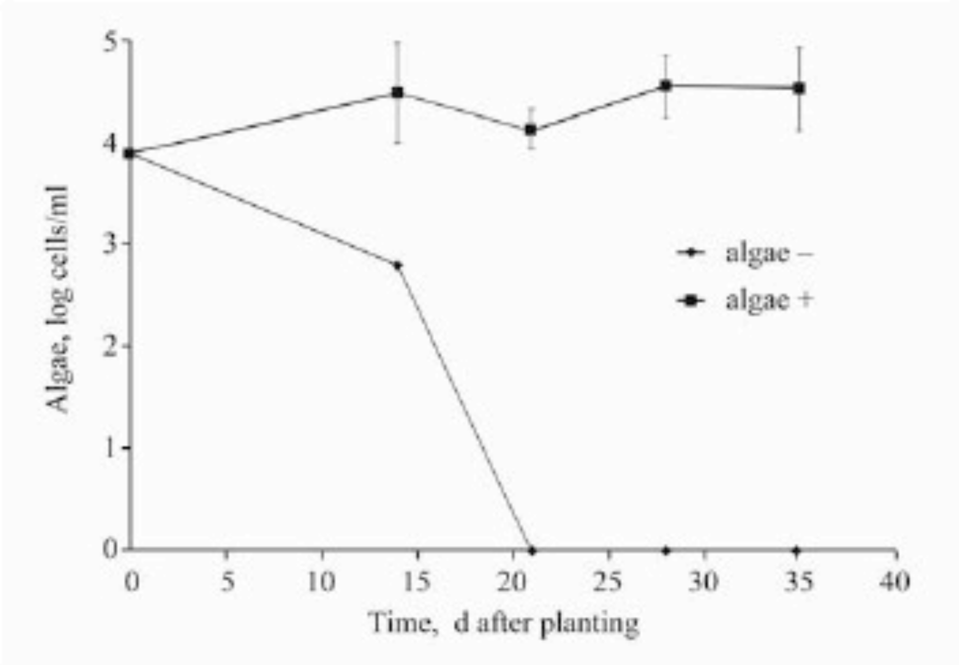

Fig. 1. Algal density in the lettuce experiment. In the “+” treatment troughs were covered with a black/white plastic foil; in the “-” treatment troughs were not covered.

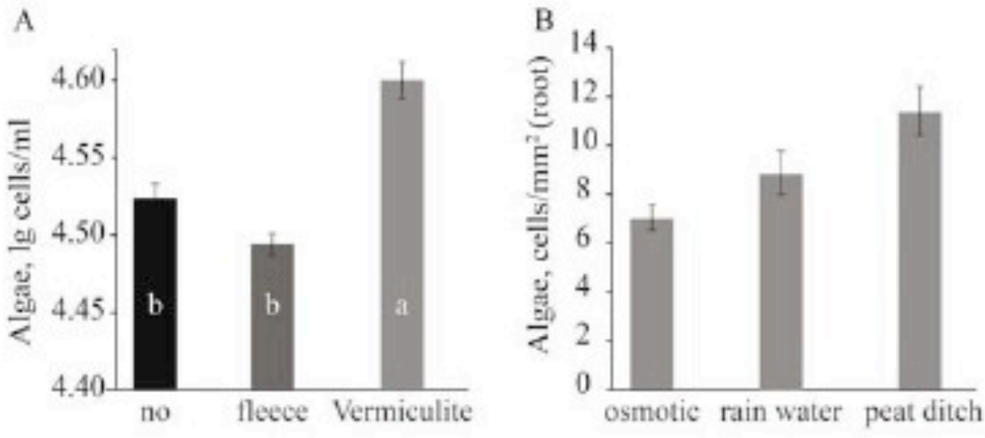

Fig. 2. Algal density three weeks after start of experiment. A: in the drain solution (lettuce experiment) when three different types of substrate were used; B: on the cucumber roots when three different water sources were used.

Prior to the start of the greenhouse experiment, the water samples exhibited a low algal diversity compared with previous results (Schwarz et al., 2005; Table 1), which were mostly obtained with Pseudodictyosphaerium spp., Scenedesmus longispina, Chlamydomonas variabilis, Chlorella vulgaris, and Klebsormidium sp. In the greenhouse studies examples of Monoraphiodium spp. and Micractinium spp. were found only in samples with water from the natural lake. Only species of Chlamydomonas spp. in lettuce and Pseudodictyosphaerium spp. in cucumber persisted throughout the experiment, and were also found later in the experiment in samples of nutrient solutions based on osmotic water. The density of the most frequently found Chlamydomonas spp. varied between 10 and 36,000 cells/ml (Fig. 3). The other algae species were found at lower densities, with a maximum of about 600 cells/ml (data not all shown). Species of Chlamydomonas are known to become dominant in closed hydroponic systems and may limit the growth of other species. Indeed, Nonomura et al. (2001) reported Chlamydomonas spp. as the prevalent algae in hydroponic systems at five different locations in Japan: depending on the location, C. reinhardtii, C. angulos, or C. umbonata were found, whereas other genera, including Ulothrix and Scenedesmus, were rare. In the present study, the troughs contained these unicellular species mentioned and in addition species of the filamentous genus Ulothrix forming large colonies within the root system (not quantified).

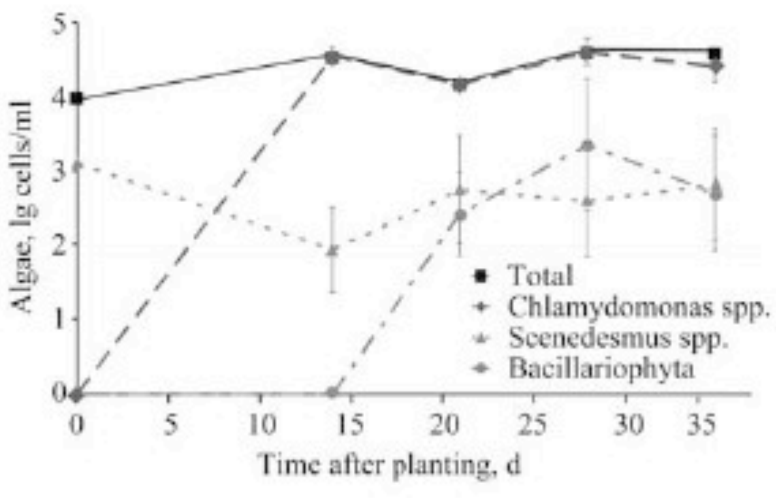

Fig. 3. Density of the three main algae species in the drain solution of the cucumber experiment.

Table 1. Occurrence of algae in different water sources investigated before start of experiments (xxx = very frequent, xx = frequent, x = rare).

Algae species	Rain water	Osmotic water	Peat ditch	Natural lake
Pseudodictyosphearium spp.	xxx	xxx	xxx	xxx
Chlamydomonas variabilis	xx	xx	xx	xx
Scenedesmus longispina	xx	xx	xx	xx
Ulothrix spp.	xx	xx	xx	
Klebsormidium spp.	xx	xx	xx	
Chlorella vulgaris			x	x
Monoraphiodium spp.				x
Micractinium spp.				x

Plant growth analysis

Algae treatment had no effect on cucumber yield but it reduced the fresh weight of the lettuce heads and cucumber shoots significantly (Fig. 4). Shoot dry matter of both plant species was also reduced. On the other hand, shoot and root dry matter percentages were greater in the treatments with algae than in those with no algae. No interactions were found between algae treatments and the other factors tested, i.e., substrate and water source. However, these two factors affected several plant growth characteristics, particularly of the root system and, therefore, the shoot/root ratio (data not shown).

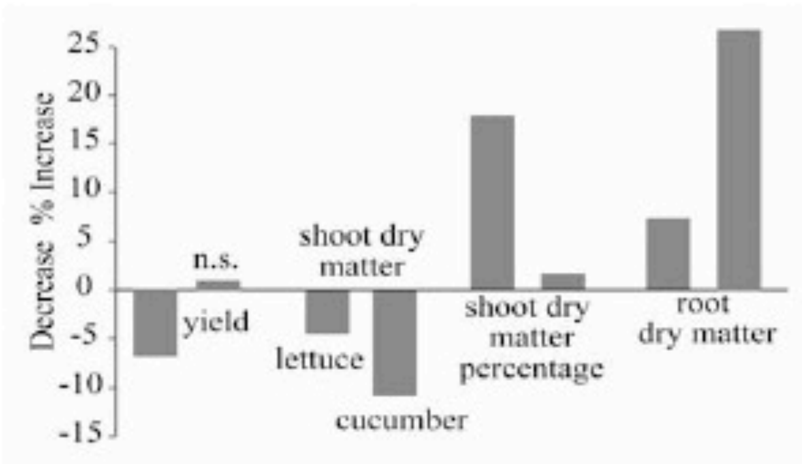

Fig. 4. Effects of algal treatment on lettuce and cucumber yields, on shoot and root dry matter contents and percentages; depicted as relative values compared with the treatments containing no algae.

Both Chlamydomonas spp. and Scenedesmus spp. are known to promote plant growth (Ördög, 1999). Chlamydomonas spp. are known to produce extracellular mucilage (Allard and Tazi, 1993), and Scenedesmus spp. reportedly exhibit weak auxin-like and cytokinin-like activity (Mazur et al., 2001). In light of the release of these hormones, plant-growth stimulation could have been expected. Indeed, in the cucumber study plant growth-promoting effects were observed, especially on the root systems of the plants. On the other hand, uptake processes were impaired in the lettuce experiment. The release of extracellular polysaccharides by Chlamydomonas spp. could have affected roots directly through their water and nitrogen uptake (Allard and Tazi, 1993). An indicator of this effect was that the specific root length was significantly reduced and the root diameter significantly increased in the A+ treatment (Schwarz and Gross, 2004). Changes in root morphology were accompanied by an increase of the total weight but not in the length of the roots, therefore, it could also be concluded that the algae released compounds other than polysaccharides that affected the roots. When investigating extract of brown algae (Ascophyllum nodosum and Laminaria hyperborea) Möller and Smith (1998) found various phenolic compounds responsible for growth inhibition of lettuce seedlings. Interestingly, at lower concentrations these compounds stimulated root growth; however, Möller and Smith (1998) did not report whether and/or how the root characteristics were affected.

In the present study, and as reported by Schwarz and Gross (2004) lettuce heads in treatment A+ showed a slight reduction of nitrogen concentration (data not shown here). It is unlikely that this reduction was caused by the competition for nutrients by the algae. Based on the nitrogen accumulation of <2.9 g/m^2/yr reported by Sirenko (1999), we calculated that algae use nitrogen at <1 g/m^2 during the lettuce production period (dry weight accumulation rate, 0.1 g/m^2/d; N concentration, 3%), which is less than 10% of the total N uptake of 15 g/m^2 by lettuce and is, therefore, insignificant for the production in a hydroponic system.

In the present study variations in root environmental conditions in the hydroponic systems affected plant roots and, to a lesser extent, algal density and composition. Similar effects on root characteristics and also on the root/shoot ratio were well described in other works (Schwarz et al., 1995; Sonneveld and de Kreij, 1999) and will not be discussed here. Although not significantly confirmed by the present data, it was observed that substrates with a large surface area, such as vermiculite, exhibited a positive relation to algal density and also to enhanced plant growth. This should be tested in further studies.

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Fertigation in Arid Regions and Saline Soils

Jeffrey C. Silvertooth

Department of Soil, Water and Environmental Science, University of Arizona, Tucson, Arizona, USA. E-mail: silver@ag.arizona.edu.

Arid lands form more than half of the arable land that is managed for agricultural purposes on the planet. Arid lands are typically characterized as having <500 mm (less than 20 inches) of annual precipitation. Worldwide, these regions exhibit very diverse ranges of conditions and of plant and animal communities, i.e., they are characterized by considerable biological diversity. Soils of arid and semi-arid areas are mostly alkaline in nature and many are also salt and/or sodium (Na) affected. Soils of arid regions are typically very highly saturated in bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Soils in arid regions have played a unique role in history. The rise and fall of several ancient civilizations has been tied to irrigation systems and the subsequent management or mismanagement of these systems. Therefore, our knowledge of previous mistakes from other civilizations can enable us to avoid repeating errors in management of arid regions for agricultural purposes and irrigation systems in the future.

Because irrigation is an important factor in the management of agricultural systems in arid lands, the application of fertilizers and nutrient inputs in the irrigation water (fertigation) is a common and increasingly important practice. Fertigation provides an opportunity to optimize the efficiency of an agricultural production system with respect to water management and the input of fertilizer nutrients. There are several critical factors that need to be considered in connection with the management of arid region soils and the practice of fertigation, these include: 1) management of salinity and sodicity in soils; 2) knowledge of crop-specific water requirements, and appropriate water management; 3) the understanding and utilization of crop nutrient requirements; and 4) the integration of these factors in a systems management approach. This integrated approach should encompass, especially, management of the uptake and utilization of water and nutrients, and the management of soil salinity and sodicity with respect to the specific crops being grown.

Many arid regions are located in latitudes with warm or hot climates, therefore, they offer the potential for growing a very broad, diverse and productive range of crops. Irrigation systems are also highly varied in arid regions around the world, the most commonly used being surface and furrow irrigation. Other common methods of irrigation include overhead sprinkler, drip, and border-surface flood irrigation. Each of these major types of irrigation systems encompasses several variations of methods. For example, furrow surface irrigation may involve application of irrigation water in every row or in alternate rows. The latter is quite commonly employed in relation to management of soluble salts in the beds.

Water quality is a critical factor with regard to the capacity and productivity of a given irrigation and crop production system. One of the primary factors associated with the quality of irrigation water is the amount of salt that it carries. The usual criterion for evaluating salinity with respect to water quality is the electrical conductivity (EC_w), which is a common measure of the salt load and the salinity level, which might be critical in relation to a crop production system. The usual units of measurement are either decisiemens per meter (dS/m) or millimhos/centimeter (mmhos/cm); a saline soil is defined as one that has an EC of the soil extract (EC_e) >4 dS/m. However, the growth of salt-sensitive crops, which include many vegetable crops, will be adversely affected at salinity levels below this definition level. In the application of fertilizers with the irrigation water, the management of soil salinity becomes increasingly critical, therefore, the quality of the irrigation water becomes a primary consideration. If the quality of the irrigation water is such that it carries fairly high concentrations of soluble salts, extra caution should be used in applying fertilizers with this irrigation water (fertigation). With respect to the irrigation water quality, EC_w values of <0.7 dS/m will not present a problem or restrict the use of irrigation water. Waters with EC_w levels of 0.7-3 dS/m necessitate a slight to moderate restriction on irrigation use, and those with EC_w values >3 dS/m pose a more serious or severe threat in this context. Thus, the application of fertilizers in irrigation water should be done in strict accordance with the quality of that water. The level of salinity in the irrigation waters must be recognized very quickly, and the impact of the addition of fertilizers on their salinity must be determined with respect to the introduction of the overall salt load into the field in question.

In all cases, water quality and the application of fertilizer nutrients need to be managed collectively to take account of the leaching process. The leaching fraction (LF) is, therefore, an important factor to be included in the overall irrigation requirements for the crop, above and beyond consideration of consumption by the crop. The interaction of the irrigation water with the fertilizers that are applied with these waters can be an important consideration with respect to the LF required for both short- and long-term management of the fields in question.

A saline soil is not a sodic soil; the latter is a non-saline soil that has a relatively large amount of exchangeable Na on the cation exchange complex (CEC), and it is defined as a soil having an exchangeable sodium percentage (ESP) >15. Another characteristic of a sodic soil is a sodium absorption ratio (SAR_e) ≥13. A soil with a high concentration of exchangeable Na will tend to disperse, leading to a breakdown of soil particle flocculation; surface crusting is common. The end result is a reduction in infiltration and permeability which, in turn, reduces the effectiveness of the applied irrigation water and also of any nutrients that it may contain. Therefore, it is important to take into account the salinity and sodicity of a soil, when considering the application of fertilizer nutrients with the irrigation water. Very commonly, the source of the Na loading that can create sodic soil conditions in a field is the irrigation water. Fertilization practices that involve the irrigation water can also influence relative Na concentrations. If a soil becomes sodic the exchangeable Na needs to be reduced through the use and application of an amendment material. This can be done similarly to fertigation, particularly if the source of Na is in the irrigation water. If the irrigation water does not contain excessive amounts of Na the reclamation procedure with the amendment should involve direct applications to the soil. The most common approach to the reclamation of a sodic soil is by the application of soluble calcium (Ca) in the form of calcium sulfate ($CaSO_4$). Calcium that is released from the $CaSO_4$ exchanges with the Na on the cation exchange complex, thus removing the latter, as soluble Na, into the soil solution from which it must be removed by leaching. In arid regions, soils are commonly alkaline, with a high concentration of free calcium carbonate ($CaCO_3$). Sulfuric acid (H_2SO_4) can be applied in the irrigation water, similarly to fertigation. When the H_2SO_4 enters the soil solution, the Ca^{2+} can be released from the $CaCO_3$, and can exchange with the Na on the exchange complex. The soluble Na can then be leached away and removed from the soil system. Therefore, management of both salinity and sodicity in a given field can be dealt with by means resembling fertigation practices.

Integration-System Management

A good first step in integrating a crop production system, with regard to irrigation and nutrient management, is to acquire a good understanding of the crop growth and development patterns, as functions of heat units (HUs). A description of crop growth and development in relation to HUs and crop phenology forms the basis of an important method to standardize crop growth and development among different years and among many locations. The first step in developing a phenological guideline would be to look for critical stages of growth in relation to HU accumulation. These phenological guidelines can

then be used to describe crop water use or consumptive use patterns, as related to critical stages of growth. In addition, nutrient update patterns can be described in relation to HU accumulations and critical stages in crop growth and development. Thus, the common baseline for coordinating crop water use and crop nutrient uptake is provided in the form of a phenological timeline based on HU accumulations. Variations among seasons and locations with regard to HU accumulations can be better normalized by the use of actual HU calculations rather than days after planting (DAP), for example.

Not only is it important to understand the consumptive use pattern for a given crop, and how that relates to important stages in growth and development, and to maximum or total amounts of irrigation water used; it is also important to know what the optimum thresholds are, with respect to plant-available water (PAW) for the crop in question. Crops vary tremendously with respect to their thresholds and capacity to maintain optimum growth and development under varying levels of PAW depletion. For example, cotton and melon crops may be able to maintain adequate or optimum growth and development as long as the PAW is >55%, whereas other crops, such as lettuce, broccoli, cauliflower, chilies (and peppers in general), etc., will begin to suffer water stress and to limit their growth, development and yield, when PAW levels drop below 70%. Accordingly, it is important to have a quantitative assessment of these thresholds for each specific crop, and to be able to relate those thresholds to stages of growth and to provide suitable amounts of water by irrigation, as required for consumptive use. In addition, it is important to maintain a good quantitative assessment of PAW conditions in the field throughout all stages of growth, in order to optimize irrigation efficiencies and crop water use.

With respect to nutrient management and fertigation, nitrogen (N) is one of the most dynamic and important nutrients that must be considered with respect to overall crop management and fertigation. Interestingly, in terrestrial ecosystems, water is commonly the first most limiting factor after sunlight. In most arid regions sunlight is certainly not limiting, and water obviously becomes the first most limiting factor. That issue is addressed, of course, through our efforts to irrigate a crop and to provide for consumptive use, leaching, and overall crop needs. The next most limiting factor in a terrestrial ecosystem is commonly plant-available N. Accordingly, N is the fertilizer nutrient that is applied in the largest amounts and is required in the largest amounts by crop plants. The N cycle illustrates the many possible pathways and transformations associated with N in a soil-plant system. Therefore, we recognize the numerous potential routes of loss of N from the soil-plant system, in terms of leaching, denitrification, immobilization, volatilization, etc. Applications of fertilizer N through the irrigation water offers an opportunity to split applications so as to increase and optimize N use efficiency in the crop production system.

In any crop production system it is important to understand the crop nutrient requirements specific to that crop. Similarly, it is important to be able to establish a realistic yield goal for the crop and field in question, in relation to total nutrient needs. This is particular true for mobile nutrients in a soil-plant system. For example, as a mobile nutrient, N presents a prime example of the need to establish a yield goal and an upper limit for crop N needs. For example, we know that cotton requires approximately 32 kg of N per bale (32 kg N/bale), therefore, a yield goal of six bales/ha for a given field would require a total of approximately 192 kg N/ha. This would be the total N need for the crop. The next step would be to subtract residual soil nitrate-N levels and the nitrate-N content in the irrigation water, to obtain the approximate target goal for N fertilization for the season, assuming that we are very efficient with fertilizer use and uptake.

To utilize N fertilizer most effectively in a soil-plant system, it is also important to understand the total N uptake for the crop, and the partitioning patterns among various plant components. For example, it is important to know the total uptake in a plant in relation to partitioning among the fruit and vegetative components, in order to achieve efficient crop nutrient management. From that information one can then determine the flux rates for the crop in relation to specific nutrient uptake. The flux information, i.e., the amount of N taken up per day, can provide an understanding of the stages of growth at which nutrient uptake is at its maximum, and how those nutrients might best be managed to achieve optimum efficiency and utilization by the crop.

With the phenological guideline information for the crop in question, and the information associated with nutrient uptake, e.g., with N uptake, in particular, and flux information for that nutrient, a strategy can be developed with regard to the timing of nutrient applications in relation to specific stages of crop growth and development, HU accumulations, and the flux points associated with that nutrient and crop. Providing for nutrient inputs within the period or growth stage at whch maximum uptake occurs can maximize efficiency with respect to crop nutrient uptake and utilization. When nutrients are provided within this “optimal window” for application through the irrigation water, the real power and value of fertigation can be realized. Crops grown in arid regions offer tremendous opportunities, based on this level of water and nutrient management, to achieve the potential efficiency.

In aiming to optimize fertigation efficiencies there are two additional, very important points to consider with respect to the conservation of nutrients, particularly in arid and/or saline-soil environments. The first point is that of chemical precipitation. For example, a common method of N fertilizer applications in irrigation water has involved the introduction of anhydrous ammonia (AA) into the irrigation water, which then carries it into the field. However, precipitation reactions can take place that do not affect the availability of the N in the water, but that alter the water quality so that the relative concentrations of Na in the irrigation water are increased. This then contributes inadvertently to the development of a sodic soil, through a practice associated with fertigation. The chemistry of this process follows from the inclusion in the irrigation water of AA which, upon hydrolysis, forms ammonium hydroxide. The ammonium hydroxide then disassociates in solution releasing hydroxyl ions, that raise the pH of the irrigation water. When irrigation waters carry sufficient bicarbonate or carbonate, the precipitation of calcium carbonate ($CaCO_3$) can follow quickly. Precipitation of $CaCO_3$ from the irrigation water increases the relative concentration of the Na that is present in that irrigation water, and thus increases the SAR. This, in turn can lead to the development of sodic soil, soil dispersion, and reduced infiltration rates for the irrigation water. The end result is a sodic soil that has developed along with a reduction in the efficiencies of the irrigation and fertilization inputs to the field in question. Therefore, this practice should be avoided and/or balanced with appropriate additions of H_2SO_4 or some similar acidic medium that can be added to the irrigation water with the AA.

Another potential mechanism of N loss from irrigation waters is volatilization. The volatilization of N from irrigation waters can be significant after the addition of any ammoniacal form of N fertilizer through fertigation. It is important to consider the interaction with the quality of the irrigation water and the potential for N loss from these waters through volatilization. In irrigation waters, high pH, high carbonate/bicarbonate concentration(s) and/or low concentration(s) of complementary ions such as sulfate (SO_4^{2-}) can be important factors to consider with respect to water quality and chemistry. Experiments conducted in Arizona have shown that up to 30% of the N added as ammonium sulfate to a group of common irrigation waters can be lost through volatilization within 10 h of exposure in the irrigation water to temperatures of 30 to 35°C. These experiments also revealed losses of up to 50% of the added N when temperatures exceeded 30-35°C, and very rapid volatilization from ammonium sulfate ($(NH_4)_2SO_4$; AS) fertilizer additions were measured at 40°C. This applied to a wide range of waters, of varied overall quality, but especially to irrigation waters that contained significant amounts of SO_4^{2-}-S. In such cases, this demonstrated a common ion effect, as encompassed by Le Chatelier's

Principle. For example, when AS was added to irrigation waters high in SO_4^{2-}-S, volatilization was reduced because of this common ion affect. However, it is essential to recognize the potential for volatilization in relation to the possibility of N loss from these irrigation waters in a very short period of time, particularly under warm or hot conditions. It is also important to note that warm and/or hot conditions are common in many arid regions where crop production systems employ fertigation. Therefore, application of ammoniacal forms of N in irrigation waters should be managed so that the exposure times in the field are minimized.

Conclusion

Fertigation offers an opportunity to optimize a crop production system with respect to both irrigation and fertilization simultaneously. As discussed in this paper, important points to consider include an understanding of crop phenology, crop water use, nutrient update dynamics for the crop in question, and water quality interactions, as related to basic soil characteristics. For the best utilization and efficiency that can possibly be realized from a fertigation management approach, it is important to integrate these various factors into the overall management scheme for the soil-plant system. It is also important to be cognizant of the potential losses of nutrients (such as N) that are potentially inherent in irrigated systems in arid regions. Any crop production system in an arid region with saline soils must also include consideration of the basic principles of salinity and sodicity management, consistent with both short- and long-term sustainable goals.

Interactive Effects of Nutrients and Salinity and Drought on Wheat Growth

Yuncai Hu, Dieter Geesing, and Urs Schmidhalter

Chair of Plant Nutrition, Department of Plant Science, Technical University of Munich, Am Hochanger 2, D-85350 Freising-Weihenstephan, Germany.
E-mail: hu@wzw.tum.de.

Abstract

Spring wheat was grown in nutrient solution to study the interactive effects of macro-nutrients and salinity. Eight salinity levels were established (0, 20, 40, 60, 80, 100, 125, and 150 mM NaCl). The levels of macro-nutrients were 1.0-, 0.2-, and 0.04-strength Hoagland macro-nutrients (× HS). Interactive effects of nitrogen and water supply on the yield of winter wheat grown in sandy soil were investigated in the field. Drought was induced by withholding rainfall for one month during the vegetative growth period. The irrigated treatments received 100 mm of water more than the control treatment, which received only normal rainfall. A consistent decrease in above-ground dry weight with increasing salinity was observed at all levels of macro-nutrients. This decrease was partly counterbalanced in plants provided with high macro-nutrient levels, especially when the nutrients became a limiting factor. Thus, the present data suggest that improved fertilization management can alleviate growth inhibition caused by salinity, only at increased levels of macro-nutrients. Under drought and normal-rainfall conditions, increased application of N fertilizer did not affect grain yield, whereas under irrigated conditions there was significantly increased grain yield with increasing N application. Our studies suggest that increased nutrient supply will not improve plant growth when the nutrient is already present in sufficient amounts in the soil, and when there is severe drought or salt stress.

Keywords: calcium, field experiment, hoagland nutrient solution, N fertilizer, potassium.

Introduction

The increasing frequency of dry periods in many regions of the world, and the problems associated with salinity in irrigated areas frequently result in the consecutive occurrence of drought and salinity on cultivated land. Currently, 50% of all irrigation schemes are affected by salinity (Ghassemi et al., 1995;

Hillel, 2000). Nutrient disturbances under both drought and salinity reduce plant growth by affecting the availability, transport and partitioning of nutrients. However, drought and salinity can differentially affect the mineral nutrition of plants (Hu and Schmidhalter, 2005). Salinity may cause nutrient deficiencies or imbalances because of the competition of toxic Na and Cl ions with nutrients such as K, Ca and NO_3. Drought, on the other hand, can affect nutrient uptake and impair acropetal translocation of some nutrients. A better understanding of the role of mineral nutrients in plant resistance to drought and salinity will contribute to improved fertilizer management in arid and semi-arid areas and in regions suffering from temporary drought.

Materials and methods

Salinity versus macro-nutrients

Seven-day-old seedlings of spring wheat (Triticum aestivum L. cv. Lona) were transplanted to polyethylene containers filled with 30 l of nutrient solution. The experiment was conducted in growth chambers. Eight salinity levels were established: 0, 20, 40, 60, 80, 100, 125, and 150 mM NaCl. The levels of macro-nutrients were 1.0-, 0.2-, and 0.04-strength Hoagland macro-nutrients (× HS). The above-ground dry weight per plant was measured at final harvest. Dried flag and second leaves from the plant top at final harvest were chosen for analysis of ion (K and Ca) concentrations, which were determined with an ICP model Liberty 200 inductively coupled plasma emission spectrometer (Varian Australia, Mulgrave, Victoria, Australia).

Drought versus N fertilizer application

The interactive effects of nitrogen and water supply on the yield of winter wheat grown in sandy soil in the field were determined. Drought was induced by withholding rainfall for 1 month during the vegetative growth period. The irrigated treatments received 100 mm of water more than the control treatment, which received only normal rainfall. Grain yield was determined at final harvest.

Results and discussion

Above-ground dry weight is defined as the sum of leaf, stem, chaff, and grain dry weights. The results in Fig. 1 demonstrate a consistent decrease in above-ground dry weight with increasing salinity, at all levels of macro-nutrients. This decrease was partly counterbalanced in plants provided with high macro-nutrient levels, especially when the nutrients became limiting factors (e.g., at 0.04 × HS). Thus, the data here suggest that improved fertilization management can alleviate growth inhibition due to salinity only at the increased levels of macro-nutrients.

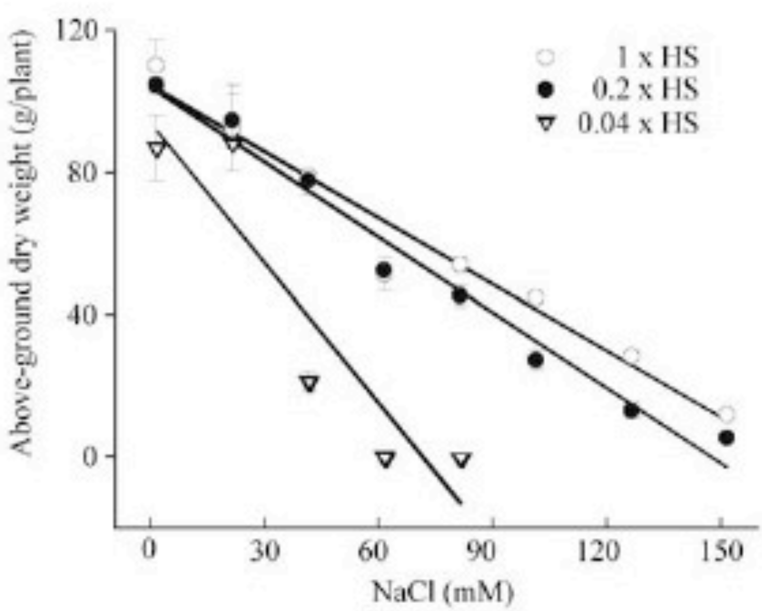

Fig. 1. The interactive effects of salinity and macro-nutrient levels on above-ground dry matter at the final harvest of spring wheat. Error bars represent standard deviations.

Fertilization management alleviated growth inhibition caused by salinity only when the macro-nutrients were increased. The potassium concentration in leaves decreased with increasing salinity (Fig. 2). Raising the macro-nutrient level from 0.04 to 0.2 × HS significantly increased the K concentration in leaves under saline conditions, but raising it further to 1.0 × HS increased the leaf K concentration only slightly. Calcium concentration in leaves decreased with increasing salinity and decreasing macro-nutrient level (Fig. 2). At a given salinity level, however, a change in Ca concentration in leaves as the macro-nutrient level was raised from 0.2 × HS to 1.0 × HS did not enhance their above-ground dry weight.

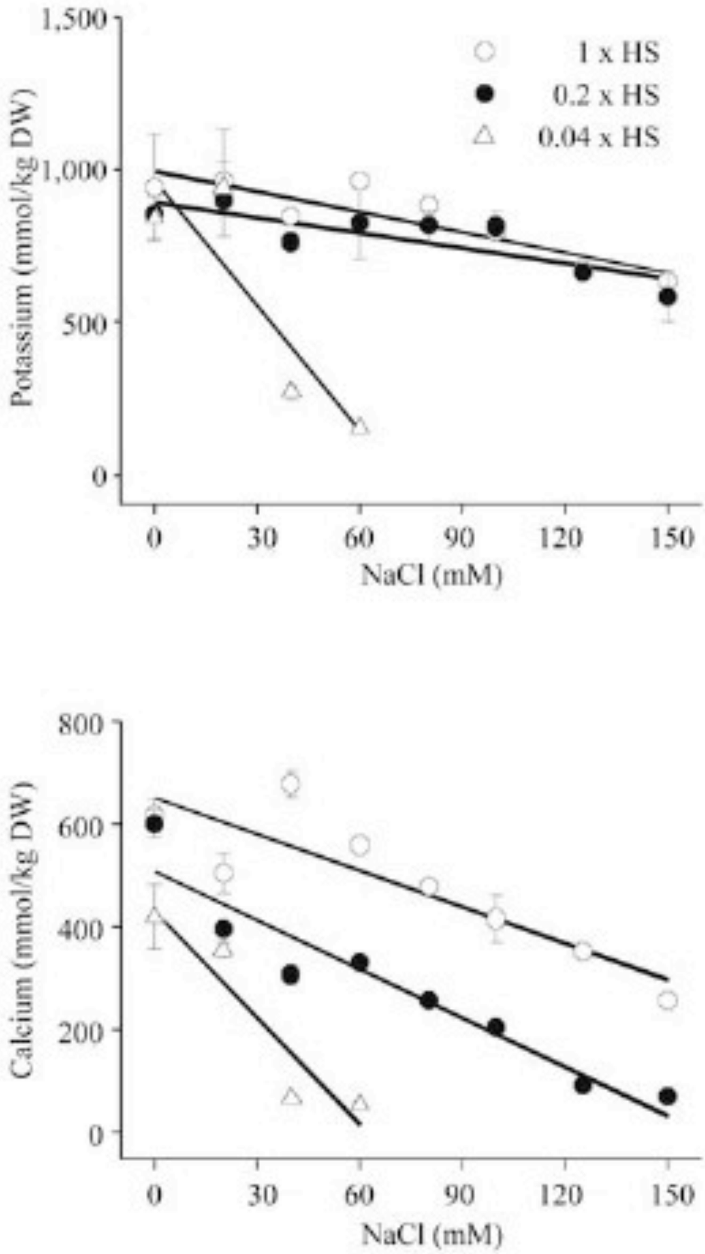

Fig. 2. The interactive effects of salinity and macro-nutrient levels on K and Ca accumulation in wheat leaves at final harvest. Error bars represent standard deviations.

Data in Fig. 3 show that under drought and normal-rainfall conditions, increased application of N fertilizer did not affect grain yield, whereas under irrigated conditions the increased N significantly increased the grain yield. As with the interactive effect of salinity and nutrients, the absence of a change in grain yield with increased N application, under drought conditions (Fig. 3) may indicate that in the present study drought limited the grain yield more severely than the N nutrition. In conclusion, the present results suggest that an increased nutrient supply will not improve plant growth when the nutrient is already present in sufficient amounts in the soil, and when the drought or salt stress is severe.

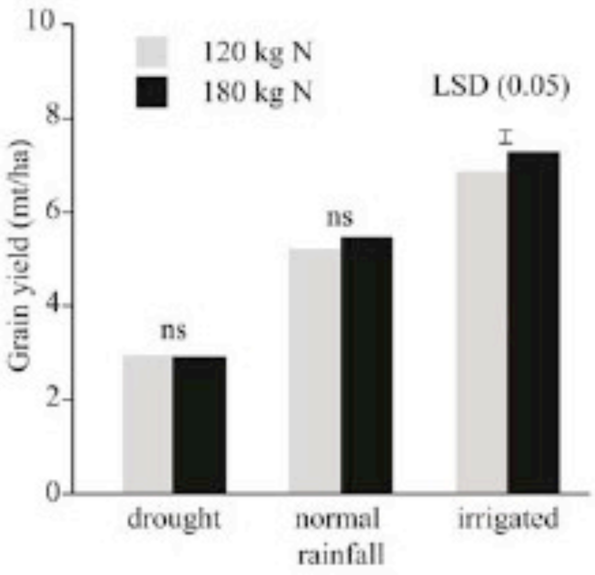

Fig. 3. The interactive effect of nitrogen and water supply on the yield of winter wheat grown in sandy soil. Drought was induced by withholding rainfall for one month during the vegetative growth period. The irrigated treatments received an additional 100 mm of water compared to the control treatment, which received only normal rainfall. Vertical bars and ns indicate LSD values at the 0.05 level and not significant, respectively.

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