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SOIL AND FOLIAR APPLICATIONS OF CALCIUM AND MOLYBDENUM TO IMPROVE BROCCOLI YIELD AND CAULIFLOWER QUALITY

presented by

RONALD VON GRUESBECK

has been accepted towards fulfillment
of the requirements for

MASTER OF SCIENCE degree in HORTICULTURE

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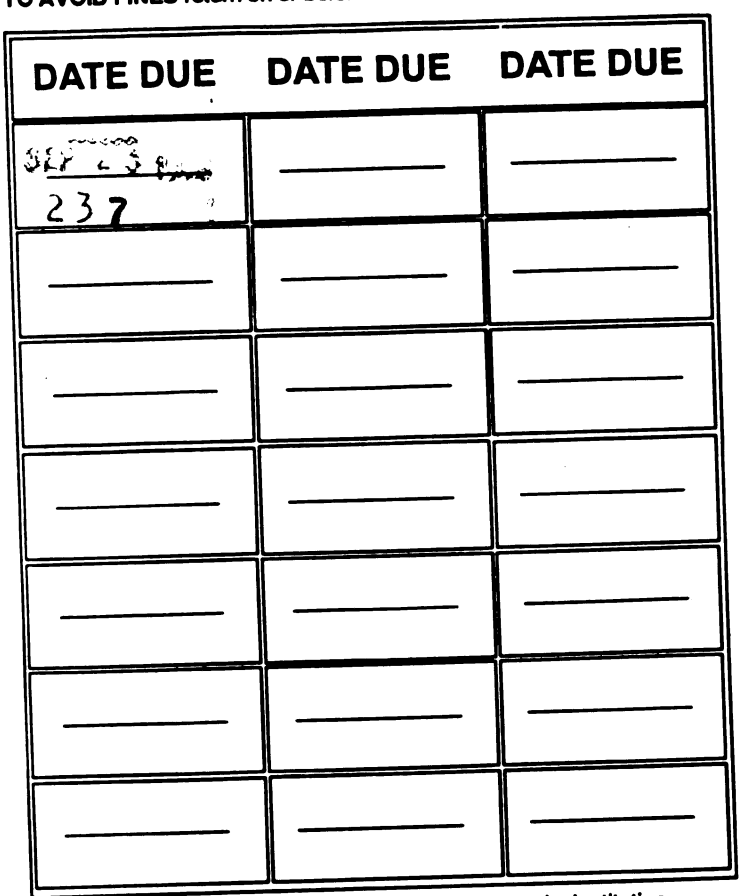

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SOIL AND FOLIAR APPLICATIONS OF CALCIUM AND MOLYBDENUM TO IMPROVE BROCCOLI YIELD AND CAULIFLOWER QUALITY

By

Ronald Von Gruesbeck

A THESIS

Submitted to
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ABSTRACT

SOIL AND FOLIAR APPLICATIONS OF CALCIUM AND MOLYBDENUM TO IMPROVE BROCCOLI YIELD AND CAULIFLOWER QUALITY

By

Ronald Von Gruesbeck

Greenhouse-grown cauliflower (*Brassica oleracea* var. *botrytis*) developed substantial tipburn when grown in a modified Hoagland's solution containing 0.5 mM calcium (Ca). With 2.0 or 8.0 mM Ca, there was minimal tipburn.

In the field, foliar-applied calcium chloride ($CaCl_2$) sprays reduced cauliflower tipburn. Soil applications of $CaCl_2$ and calcium sulfate ($CaSO_4$) resulted in higher curd Ca levels, but only $CaCl_2$ increased leaf Ca and reduced tipburn. Tipburn decreased with increasing soil Ca, but increased with increasing curd Ca. As curd Ca increased, Ca in surrounding leaves decreased.

Greenhouse-grown broccoli (*Brassica oleracea* var. *italica*) grew well with 0, 0.1, 1.0, 10, or 100 μM molybdenum (Mo) added to nutrient solutions, but 1000 μM Mo in the nutrient solution caused phytotoxicity. In the field, Mo content of broccoli leaves was higher after foliar and soil applications of Mo, but only soil applications improved yield.

Several adjuvants were tested to determine their effect on Mo uptake by broccoli leaves. Silwet L-77, an organosilicone surfactant, enhanced Mo uptake under all environmental conditions.

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INTRODUCTION

Broccoli and cauliflower are important vegetable crops in the United States. There are 700 acres of broccoli and 1700 acres of cauliflower grown in Michigan (Michigan Commercial Vegetable Survey, 1987). According to the 1982, United States Census of Agriculture, Michigan ranks 7th in broccoli acreage and 6th in cauliflower acreage in the United States.

Broccoli and cauliflower are susceptible to several nutrient deficiencies. Molybdenum (Mo) deficiency has been recognized in cole crops since about 1948. It causes symptoms similar to nitrogen (N) deficiency. This is not surprising, since Mo is an important part of the nitrate reductase system in higher plants. Molybdenum is known to be deficient in low pH soils and soils with a high iron content. When N deficiency-like symptoms occur, it is difficult to determine whether the problem is N or Mo deficiency.

Calcium (Ca) has been related to tipburn and poor leaf development in cole crops. The deficiency occurs because it is difficult to get enough Ca into the plants and to the growing points during periods of rapid growth, even when there is sufficient Ca in the soil.

The research reported here was conducted to determine the response of broccoli to Mo applications, and to increase Ca uptake by cauliflower.

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Chapter 1

REVIEW OF LITERATURE

I. CALCIUM

A. Introduction

Calcium (Ca) is an essential plant nutrient and a constituent of various soil minerals. Recently Poovaiah (1988) listed numerous Ca mediated processes, including cell division, geotropism, protoplasmic streaming, stomatal control, chloroplast movement, secretion, hormone dependent changes, enzyme activation, senescence and ripening, and protein phosphorylation. Calcium may also be involved in the regulation of the pH within plant cells (Felle, 1988), is a component of cell walls, and is required to maintain membrane integrity (Demarty et al., 1984; Jones and Lunt, 1967; Marinos, 1962; Paliyath et al., 1984,; Poovaiah and Leopold, 1973; Simon, 1978). Severe Ca deficiency results in death of plant growing points (Millaway and Wiersholm, 1979).

Even though Ca is classified as a secondary nutrient, a large quantity is taken up by plants. Citrus leaves contain twice as much Ca as nitrogen, phosphorus and potassium combined (Bar-Akiva, 1970).

Soils usually contain large quantities of Ca. However, even with large amounts of Ca in the soil, Ca deficiency

disorders develop, resulting in poor quality fruits and vegetables. Many factors are involved.

Calcium deficiency is associated with many factors and affects many crops. Collier and Tibbitts (1982) drew a diagrammatic model that begins with 17 factors that favor lettuce tipburn development. C. B. Shear (1975) lists approximately 35 disorders of fruits and vegetables that are associated with localized Ca deficiency. These Ca deficiencies develop in rapidly growing plant parts such as root tips, shoot tips, young leaves, and fruits. These rapidly growing tissues are primarily supplied by the phloem, which contains very little Ca (Wiersum, 1966).

High levels of Ca in the soil are necessary for optimal plant growth. Calcium is absorbed by the entire root system, but is only translocated from just behind young root tips (Clarkson, et al., 1968) and it does not appear to be remobilized in the plant when Ca stress occurs (Loneragan and Snowball, 1969a). Higinbotham et al. (1967) used the Nernst equation to predict Ca uptake by barley and pea roots. The predicted uptake was 100 to 1000 fold greater than the experimentally determined uptake, suggesting exclusion or exudation of Ca.

B. Soil and Foliar-applied Calcium

Many fertilizer materials contain Ca. Superphosphate contains 18 to 21% Ca and triple superphosphate contains 12 to 14% Ca. Liming materials such as pure lime, hydrated

lime, calcitic limestone, dolomite and marl are the major sources of soil applied Ca. Liming materials may vary in Ca content due to impurities. Pure lime, hydrated lime, calcitic limestone, and dolomite contain approximately 87, 54, 40, and 22% Ca respectively. Marl is a calcium carbonate ($CaCO_3$) and soil mixture. Calcium sulfate ($CaSO_4 \cdot 2H_2O$), commonly called gypsum, contains up to 29% Ca depending on its purity and hydration state. Although calcium nitrate ($Ca(NO_3)_2$, 24% Ca), calcium chloride ($CaCl_2$, 36% Ca) and calcium hydroxide ($Ca(OH)_2$, 54% Ca) may be applied directly to the soil, they are well-suited for use in aqueous solutions because they are water-soluble. Calcium chelate is also water soluble, but does not appear to be a superior Ca source (Neilsen et al., 1985).

When lime is applied to achieve a desired pH, it not only raises soil pH, it also supplies Ca. It is generally thought that as long as the pH is kept within the recommended range for the crop being grown, additional Ca is not needed.

Calcium sulfate is used as a source of both Ca and sulfur. It is not used to change soil pH. Although it is not standard practice, some crops will grow almost as well on an acid soil amended with $CaSO_4 \cdot 2H_2O$ as with lime (Inoue et al., 1988). In some cases it may be desirable to add Ca to the soil without raising the pH. The addition of $CaSO_4 \cdot 2H_2O$ to soils that are low in Ca, but do not have a low pH is an established practice in peanut production

(Bell, 1985; Hartzog and Adams, 1983; Walker and Keisling, 1978). Calcium sulfate is also a common material for the reclamation of sodic soils. The sodium in a sodic soil disperses the clay particles, making the soil virtually impervious to roots, air, and water. When $CaSO_4 \cdot 2H_2O$ is added, Ca replaces sodium on the soil exchange sites. This allows the clay particles to flocculate, which improves the soil pore size distribution. Subsequent water percolation leaches the excess sodium ions from the soil (Hawkes at al., 1985). Calcium sulfate can also be used with lime to reduce exchangeable aluminum, a toxic element that reduces Ca uptake, in Oxysols (Pavan et al., 1984).

Soil applications of $CaSO_4 \cdot 2H_2O$ do not seem to prevent tipburn. Immature cauliflower leaves contained more Ca when $CaSO_4 \cdot 2H_2O$ was applied to the soil, but there was not a significant decrease in tipburn (Rosen et al., 1987).

Soil applied $CaCl_2$ is more likely to injure plants than $CaSO_4 \cdot 2H_2O$, because it enters the soil solution rapidly and provides two moles of Cl for each mole of Ca. Applying $CaCl_2$ provides a short burst of Ca that quickly leaches from the soil (Gupta and Singh, 1988). When Islam et al. (1987) compared the effect of $CaCl_2$ and $CaSO_4 \cdot 2H_2O$ on the growth of plants in solution culture, they found maximum plant growth was obtained at a higher solution Ca concentration using $CaSO_4 \cdot 2H_2O$ than $CaCl_2$. They concluded that the plants were injured by Cl before the optimum Ca concentration was reached.

There has been some success in overcoming localized Ca deficiency by applying soluble Ca. The Ca solution is applied in the field or post harvest. For example, celery blackheart (Geraldson, 1954) and Chinese cabbage tipburn (Hori et al., 1960) have been controlled in the field with Ca sprays and apples are sometimes dipped after harvest with a Ca solution to reduce bitter pit (Bangerth et al., 1972). Eisinger and Bradford (1986) increased the Ca concentration of snap bean seed with foliar applications of a commercial Ca formulation.

Applying $CaCl_2$ could affect Ca translocation. The transpiration rate of apple leaves was reduced for 2 days following $CaCl_2$ application (Swietlik and Miller, 1987). This should have an effect similar to raising the relative humidity (RH) which is discussed in another section.

The effectiveness of foliar Ca applications is limited because they must be applied frequently and directly to the affected plant part. Some crops develop Ca disorders, such as internal tipburn of cabbage, which cannot be reached by sprays. In addition, Ca uptake through leaf cuticles is minimal (Chamel, 1984).

C. Calcium Uptake and Translocation

Calcium moves through the soil to the plant roots by mass flow and diffusion. In simple terms, mass flow of Ca can be defined as Ca moving with the soil solution to the plant roots, and diffusion of Ca can be defined as Ca moving

through the soil solution to the plant roots. When mass flow (i.e. water uptake) to the roots exceeds Ca uptake, Ca accumulates in the vicinity of the roots (Barber and Ozanne, 1970). Elgawhary et al. (1972) found when tomato plants were grown at a high RH, diffusion was dominant, but when the plants were grown at a low RH, mass flow was dominant. Once Ca reaches the roots it is absorbed onto exchange sites. The exchange capacity of the root may be an important parameter affecting Ca uptake (Knight et al., 1961). Calcium probably moves to the xylem through the apoplastic route. Root sections that are suberized block the apoplastic route and restrict Ca movement to the xylem (Ferguson, 1979). Because Ca uptake seems to be controlled, Macklon and Sim (1981) believe that at some point Ca must pass through the symplast before entering the xylem, probably at the endodermis. Chino (1979), studying 10 day old plants, found soybean roots accumulated Ca on the root surface while maize roots accumulated Ca at the endodermis. This could indicate that while the endodermis may restrict Ca flow in maize roots it does not restrict Ca movement in soybean roots.

At one time it was thought that Ca was translocated within the plant by mass flow, i.e. Ca simply moving with the xylem stream (Hanger, 1979). Now Ca is thought to move by exchange because Ca movement lags behind water flow (Biddulph et al., 1961), nonionic Ca such as Ca chelate moves more freely than the ionic (Ca^{+2}) form (Bradfield,

1976; Ferguson and Bollard, 1976; Hanger, 1979; Jacoby, 1967; Millikan and Hanger, 1964; van de Geijn and Petit 1979), and introduction of other divalent ions into the xylem stream promotes Ca^{+2} movement (Bell and Biddulph, 1963; Ferguson and Bollard, 1976; Hanger, 1979; Millikan and Hanger, 1964, 1967; Shear and Faust, 1970). Sometimes mass flow does appear to be important. When bean plants were grown in one-twentieth strength Hoagland's solution, there was no significant increase in shoot uptake of Ca, when the transpiration rate increased 7.7 times. When the plants were grown in half-strength Hoagland's solution, shoot Ca uptake increased 2.4 times when the transpiration rate increased 5.8 times. Calcium absorbed and adsorbed by the roots was not affected by the transpiration rate (Drew and Biddulph, 1971). Mass flow appeared to be important when a half-strength Hoagland's solution was used.

For Ca to reach developing tissue, it must leave the xylem vessels. Levi (1968) found that ^{45}Ca taken up by the roots moved into the main veins of bean leaves, then progressed to the small veins. Only after ^{45}Ca had moved through the entire network of veins did ^{45}Ca enter the leaf mesophyll. There are indications that Ca movement into leaves is controlled by some mechanism such as a physical barrier. Bean leaves reached a maximum Ca accumulation rate when they were 13 days old. Transpiration rate and nutrient solution strength did not affect Ca accumulation (Koontz and Foote, 1966). Wiebe et al. (1977) found that cabbage

transports ^{45}Ca to the inner leaves during the night and the outer leaves during the day. They concluded that Ca containing xylem sap is moved as the cabbage head shrinks and swells.

It is possible that hydrostatic gradients or root pressure encourage Ca movement through the apoplast surrounding the young leaf or root tissue where xylem vessels are undeveloped. Steudle (1989) concluded that in roots water moves primarily in the apoplast under hydrostatic gradients, while osmotic gradients increase cell to cell movement through the symplast.

Because Ca is present in the phloem (Bangerth, 1979; Eschrich et al., 1964; Ferguson, 1979; Hanger, 1979; Läuchli, 1968; Millikan and Hanger, 1969; Pate et al., 1975; Priestly, 1976; Ringoet et al., 1967; Ringoet et al., 1968; Stebbins and Dewey, 1972; Tammes and van Die, 1964; Thomas, 1967; Wieneke, 1979; Wiersum et al., 1971), it is possible that some Ca is transported by the phloem. However, its movement in the phloem appears to be limited. There is no evidence that Ca redistribution will overcome Ca disorders. Bean plants moved from complete nutrient solutions to those without phosphorus, potassium, or Ca were able to continue to grow in solutions lacking P or K, but the growing points and small leaves on plants grown without adequate Ca died (Ascencio, 1988). Loneragan and Snowball (1969a) found that plants grown in a high Ca solution became Ca deficient when transferred to a low Ca solution even though a large amount

of previously accumulated Ca was present in the older leaves.

Whether Ca uptake and translocation is passive or active has been debated. Ca uptake by intact or excised roots is generally much less than would be expected for active uptake (Higinbotham et al., 1967; Kirkby, 1979; Maas, 1969; Moore et al., 1961). Maas (1969) believes that Ca uptake by maize roots becomes active when the external Ca concentration is low. Probably Ca enters the root cytoplasm passively and is pumped back out to the apoplast (Bengtsson and Jensén, 1982; Macklon and Sim, 1981). Drew and Biddulph (1971) found that metabolic inhibitors affected Ca uptake very little, but strongly inhibited Ca translocation to the shoot.

D. Factors Affecting Calcium Nutrition and Tipburn Development

1. Root growth. Some researchers believe that Ca is only transported from the very young, unsuberized root tips (Clarkson et al., 1968; Harrison-Murray and Clarkson, 1973). Once suberin develops it prevents Ca from entering the xylem. This suberized region is called the Casparian band. Clarkson et al. (1968) found that the entire root absorbed Ca, but Ca was primarily transported from the root tip area.

The length of young, unsuberized root tissue behind the root tip is dependent on the rate of root growth (Peterson, 1988). If the root grows slowly, suberin develops close to the root tip. If the root grows rapidly, there is a longer

unsuberized section at the end of the root. Consequently, rapid root growth may increase Ca uptake.

The environment in which the plant grows will affect the root growth rate and the root to shoot ratio. In fact, the Ca concentration surrounding the root is an important determinant of root growth rate. Root growth increases when Ca concentration increases (Burström, 1954), and an uninterrupted supply of Ca is needed for good root growth. Because calcium is not transplanted to root tips from other plant parts (von Marschner and Richter, 1974), the root tips will die if Ca is not externally available, (Millaway and Wiersholm, 1979). Within minutes after Ca is unavailable, there are observable changes in roots (Epstein, 1988).

The findings of studies such as the one by Clarkson et al. (1968) may not be applicable to mature plants, because the roots of seedling plants were used to determine the root area where Ca uptake occurs. This could be a serious flaw. A recent study on water uptake by maize roots (McCully and Canny, 1988) found that water was taken up by the old and very young root sections. In young seedlings, such as those used in Ca uptake studies, the old root sections were not present. Therefore absorption and translocation of Ca from fully mature roots cannot be ruled out.

2. Shoot growth. Rapidly growing tissues are especially prone to Ca deficiency. If the growth rate exceeds the rate of Ca uptake for even a short period of time, the new growth will become Ca deficient (Loneragan and

Snowball, 1969b). Thibodeau and Minotti (1969) had suggested that the fastest growing lettuce leaves were the ones that tipburn. Their hypothesis was confirmed by Collier and Huntington (1983). Ulrich and Mostafa (1976) state that tipburn is a welcomed sign to sugar beet growers because it occurs during rapid growth and indicates that a good harvest will follow. Carrots develop leaf necrosis during rapid growth in growth chambers (Tibbitts et al., 1983). Cabbage tipburn has also been noted during periods of rapid growth (Nieuwhof et al., 1960).

Cauliflower tipburn usually occurs during a period beginning just before the heads are visible until harvest. Growth rate may be an important factor. Hand and Atherton (1987) found the rate of cauliflower leaf initiation during the mature phase was almost three times what it was during the juvenile phase when measured on a thermal time base. Most or all factors listed below affect shoot and root growth rate.

3. Soil calcium concentration. Many experiments have shown that adding Ca to the substrate will increase Ca concentration in the plant, often accompanied by reduced Ca deficiency symptoms. This holds true for plants grown in solution and sand culture (Ascencio, 1987; Edwards and Horton, 1983; Geraldson, 1957; Islam et al., 1987; Loneragan and Snowball, 1969a; Maynard et al., 1957; Maynard and Barker, 1972; Maynard et al., 1965; Maynard et al. 1981; Rossi et al., 1988; Staub et al., 1988), and for plants

grown in soil in the greenhouse (Clarkson, 1965; Sonneveld and van den Ende, 1975; Sonneveld and Mook, 1983) or in the field (Bell, 1985; Farina and Channon, 1988; Geraldson, 1957; Punja et al., 1986; Rossi et al., 1988). Maynard et al., (1981) found increasing the concentration of Ca in the nutrient solution increased the Ca concentration of cauliflower leaves and reduced tipburn severity and curd discoloration.

4. Other plant nutrients and total nutrient concentration. Other plant nutrients can reduce or increase Ca uptake and translocation. Excess salts and a small Ca to total cation ratio reduces Ca uptake (Geraldson, 1957). In some cases applying magnesium (Mg)-containing lime can reduce Ca uptake even though the lime has added Ca to the soil (Pavan et al., 1987). In a nutrient culture experiment, barley seedlings took up more Mg as the concentration of Mg in the solution increased. The same was true for Ca, but Mg uptake was more responsive (Lazaroff and Pitman, 1966). Solution culture experiments have shown that increasing the concentration of nutrients, often including Ca, decreases the uptake of Ca (Bradfield and Guttridge, 1979; Bradfield and Guttridge, 1984; Ehret and Ho, 1986; Erlandson and Jensén, 1989; Gubbles and Carolus, 1971; Guttridge et al., 1981; Hori et al., 1960; Mason and Guttridge, 1975) and increases the incidence of celery blackheart (Gubbels and Carolus, 1971), strawberry leaf tipburn (Bradfield and Guttridge, 1979; Guttridge et al.,

1981; Mason and Guttridge, 1975), and tomato blossom end rot (Ehret and Ho, 1986). Koontz and Foote (1966) found when they increased the concentration of all nutrients equally, the uptake of Ca was unchanged. Ehret and Ho (1986) found that as they increased solution conductivity from 2 mS to 17 mS by increasing the concentration of several nutrients, including Ca, the Ca concentration in the roots increased while the Ca concentration of the shoots decreased.

Increasing solution concentration may, in part, increase Ca deficiency by decreasing root pressure. High solution concentrations decrease water as well as Ca uptake (Ehret and Ho, 1986). Using concentrated nutrient solutions on strawberry plants during the night decreased guttation, decreased Ca concentration in emerging leaves, and increased tipburn (Guttridge et al., 1981). Bakker and Sonneveld (1988) investigated the interaction of RH, solution concentration, and Ca percentage of cations on Ca uptake and leaf necrosis of cucumber. As Ca made up a larger percentage of the cations RH became unimportant. As solution concentration decreased RH became less important. They found low RH decreased Ca deficiency symptoms. Humidity and its influence on Ca uptake and Ca deficiency will be explored further in another section.

Nitrogen may affect Ca nutrition by altering the root to shoot ratio. High nitrogen fertilization favors cabbage tipburn (Nieuwhof et al., 1960). This could be due to increased growth. Nitrogen stimulates shoot growth more

than root growth (Kuchenbuch et al., 1988). Because increasing nitrogen levels increases shoot growth more than root growth, the uptake of Ca might not keep pace with the increased demand for Ca.

Nitrogen fertilizers can alter the Ca content of the soil solution. Nitrogen applied as Ca nitrate ($Ca(NO_3)_2$) or ammonium nitrate (NH_4NO_3) increases Ca^{+2} diffusion (Mullins and Edwards, 1987). In another study, ammonium sulfate ($(NH_4)_2SO_4$) and NH_4NO_3 increased the soil solution concentration of Ca^{+2} in a calcareous soil while ammonium hydroxide (NH_4OH), ammonium carbonate ($(NH_4)_2CO_3$) and diammonium phosphate ($(NH_4)_2HPO_4$) reduced the Ca^{+2} content of the soil solution. Diammonium phosphate was especially effective at lowering the Ca^{+2} content of the soil solution (Fenn and Wu, 1987).

Nitrogen is taken up by plants in more than one form. Nitrate stimulates Ca uptake while NH_4^- depresses Ca uptake by Chinese cabbage (Hori et al., 1960) and broccoli (Shelp, 1987a). However, Shear and Faust (1970) found while NO_3^- stimulated Ca uptake and accumulation in mature apple leaves, NH_4^+ increased Ca movement into new leaves where Ca deficiency would be more likely to occur.

Certain micronutrients, such as boron (B) and molybdenum (Mo), may also effect Ca uptake and Ca deficiency symptoms. Kuo et al. (1981) found low B and low Ca produced more tipburn on Chinese cabbage than having only one of the nutrients low. Kheshem et al. (1988) found 0.2 ppm Mo vs.

no added Mo increased Ca uptake of tomato fruits, while Wallace (1979) found excess Mo (10 mM) reduced Ca in bean roots, stems, and leaves.

5. Soil compaction and reduced soil volume. Soil compaction and reduced soil volume will reduce root growth (Russell and Goss, 1974). Chinese cabbage root growth was restricted by growing it in 0.5 or 3.0 liter pots. They developed tipburn and the young leaf tissue contained less Ca than the plants grown in 10 liter pots. Even when the plants grown in the small pots were watered with 10 mM $Ca(NO_3)_2$ or $CaCl_2$ they developed tipburn (Aloni, 1986). Lettuce grown in the outer rows of beds four rows wide developed much more tipburn than lettuce grown in the inner rows. Furthermore, irrigation and misting reduced tipburn in the inner rows but not in the outer rows. The authors concluded that soil compaction in the wheel tracks could have reduced root growth in the outer rows (Cox and Dearman, 1981).

6. Soil moisture. Soil moisture can affect Ca uptake in several ways. A waterlogged soil can stop root growth, because it becomes anaerobic. Many plant species require oxygen (0_2) in the root zone for root growth. On the other hand, when the soil becomes anaerobic, the Ca content of the soil solution will rise as dissolved carbon dioxide (CO_2) concentration increases and solubilizes Ca. In a waterlogging study of cotton, the waterlogged plants had less Ca in the stems but leaf Ca was not affected (Hocking

et al., 1987). Restricted soil aeration reduced Ca concentration in pecan seedling leaves and trunks. Smith et al. (1989) concluded that decreased root volume may have reduced Ca uptake. It is unknown how various periods of waterlogging affect cauliflower tipburn.

As soil moisture reaches field capacity, Ca uptake probably increases. Adequate soil moisture increases root growth (Barber et al., 1988), and promotes root pressure by decreasing soil osmotic potential. A higher water content in the soil also decreases soil Ca solution concentration (Larsen and Widdowson, 1968). Increased root growth, root pressure, and decreased ionic concentration promote Ca uptake as discussed in separate sections. However, the effects listed above may be balanced by the fact that the concentrations of divalent cations such as Ca decrease more than the monovalent cations as soil moisture increases (Larsen and Widdowson, 1968) and the root to shoot ratio may increase under water stress (Brouwer, 1983).

As the soil becomes dryer, the reverse of the above takes place. The soil osmotic potential increases as the soil dries or the salt concentration increases. Haber et al. (1983) studied the effect of osmotic potential on Ca uptake by peach seedlings. They varied solution osmotic potential with polyethylene glycol (PEG-4000). Root growth, shoot growth, water uptake, and Ca uptake decreased when the seedlings were stressed by raising the osmotic potential. The ratio of water uptake to Ca uptake remained constant.

The number and length of young roots decreased under stress. The authors concluded that Ca absorption is related to the amount of unsuberized root surface present.

Furthermore, according to Dalton (1988), water can be taken up in the vapor phase. In a dry soil, plant nutrients present in the vapor phase, such as water and ammonia (NH_3), might continue to be taken up to a limited extent. Little Ca uptake would be expected under these conditions, because Ca is a dissolved solid and will not be present in the vapor phase.

7. *Humidity*. Humidity is very important in tipburn development. Relative humidity may be especially important for *Brassica* spp. because cabbage stomata do not close at night (Tibbitts and Palzkill, 1979). Both high humidity and low humidity can promote Ca deficiency. When strawberry plants were grown at 95% RH, the emerging leaves contained about one third the Ca they contained if the plants were grown at 65% RH (Mason and Guttridge, 1975). High RH also increased the incidence of pillowy, which is "opaque white, porous-textured" cucumber fruit tissue that is indicative of calcium deficiency, (Staub et al., 1987, 1988) and lowered the Ca concentration in cucumber fruit (Staub et al., 1987). On the other hand, carrots grown under high RH did not have leaf necrosis while those grown under a lower RH did. The unfolding leaves contained 50% more Ca than those grown under lower RH (Tibbitts et al., 1983) and low RH can promote Chinese cabbage tipburn (Kuo et al., 1981). These

conflicting results can be explained by the observation that while low RH increases Ca in Ca sensitive tissues during the light period (Collier and Tibbitts, 1984), high RH increases Ca in Ca sensitive tissues during the dark period (Collier and Tibbitts, 1984; Bradfield and Guttridge, 1984; Palzkill et al., 1976).

Low RH during the light period may increase Ca uptake and transport in the xylem by increasing the vapor pressure deficit (osmotic gradients). High RH and low solution concentration during the dark period may increase Ca uptake in tissue with low transpiration rates by promoting root pressure (hydrostatic gradients). When young cabbage plants were completely covered, providing high RH, the leaves accumulated ^{45}Ca, guttated freely, and did not tipburn. When the plants were grown uncovered at 50% RH the leaves accumulated ^{45}Ca, transpired freely, and did not tipburn. When only the inner leaves were covered, these inner leaves did not accumulate ^{45}Ca, did not guttate, and tipburned. There was no detectable ^{45}Ca at the leaf margins (Palzkill and Tibbitts, 1977). Von Krug et al. (1972) studied cauliflower and found low RH prevented young leaf tipburn, while fluctuating the water potential, especially by changing the RH, decreased the incidence of glassy curds. Glassy curds and tipburned leaves were caused by Ca deficiency in these tissues. They believe that changing the water potential promotes Ca accumulation from the xylem as the curd shrinks and swells.

8. Temperature. A sudden rise in air temperature might promote Ca deficiency of leaves by increasing shoot growth while root growth and Ca uptake remain relatively constant, because the temperature of the soil changes relatively slowly. In general, an increase in soil temperature, up to a point that is not harmful, will increase plant root (Barber et al., 1988) and shoot growth and increase Ca uptake. Very low root temperatures (-4 to 2°C) increased Ca uptake by wheat roots (Erlandson et al., 1987; Erlandson and Jensén, 1989). Enhancement of Ca uptake at these very low temperatures may have been due to root injury. Bean roots were kept at 5, 15, and 25°C, while the tops were kept at 25°C. With each 10°C increase in root temperature, transpiration and shoot uptake of Ca increased. Calcium uptake ($\mu M \cdot shoot^{-1}$) increased 26 times and transpiration (ml·plant) increased 4.5 times when root temperature was increased from 5° to 25°C (Drew and Biddulph, 1971). Low air temperatures increased the Ca content of tomato tops, but changing the root temperature did not have a significant effect on the Ca content of tomato tops (Papadopoulos and Tiessen, 1987). Collier and Tibbitts (1984) found increasing lettuce root temperature increased Ca uptake slightly, but also increased tipburn.

9. Light. Not enough research has been conducted to get a clear picture of the effect of light levels on Ca uptake and Ca deficiency. An increase in light level may promote Ca deficiency by increasing shoot growth first then

root growth. At low light levels root growth is slowed more than shoot growth. The root to shoot ratio of onion (Son et al., 1988) and soybeans (Bethlenfalvay and Pacovsky, 1983) decreased at low light levels. When the roots are growing faster than the shoots Ca deficiency would not be expected. However, lettuce tipburn was increased by high light levels (Tibbitts and Rao, 1968).

10. Indoleacetic acid. Indoleacetic acid (IAA) may play an important role in Ca transport to Ca sensitive tissues. In tomato, basipital IAA transport increased Ca transport into excised fruit even though the fruit was held in a 100% RH atmosphere (Banuelos et al., 1987). When IAA transport in lettuce was inhibited with triiodo-benzoic acid, the incidence of tipburn increased (Banuelos et al., 1988).

11. Genetics. Some cauliflower cultivars are more susceptible to Ca deficiency than others. In a study by Hochmuth (1984), the most Ca efficient cauliflower strain produced 14 times more dry matter than the least Ca efficient strain did under low Ca conditions. In a study using tomatoes, Greenleaf and Adams (1969) concluded that there were genetic differences in absorbing and accumulating Ca and in the amount of Ca absorption and accumulation required by the plant. A partial explanation for genetic differences in Ca uptake could be differences in the length of the root tips. Since the length of root tips varies with

plant species (Perumalla and Peterson, 1986), it must be, in part, genetically regulated.

II. MOLYBDENUM

A. Introduction

Molybdenum has an atomic weight of 95.95. It is one of the heaviest elements required by biological systems. Molybdenum has five oxidation states or valencies: +2 through +6. It has basic properties in the lower states and acidic properties in the higher states. The most stable valency is Mo^{+6} (Elwell and Wood, 1971). The solubility of molybdates in water ranges from the relatively insoluble alkaline earth and heavy metal molybdates such as calcium molybdate and wulfenite ($PbMoO_4$) to the readily soluble alkali metal molybdates such as potassium molybdate (Elwell and Wood, 1971).

Molybdenum was one of the last elements to be included in a group of elements considered essential for plant nutrition. In 1914, Robinson published analytical results showing Mo to be present in two of the many soil samples he analyzed. In 1917, Robinson et al. found Mo in a wide variety of plant materials. Bortels (1930) may have been the first to recognize a biological need of Mo. Using tomato plants, Arnon and Stout (1939) were the first to establish the essentiality of Mo for higher plants. Davies (1945) thought Mo might control whiptail, a disorder of

broccoli and cauliflower, and Mitchell (1945) did control whiptail with ammonium molybdate. A bibliography on the agricultural aspects of Mo nutrition was produced (Borys and Childers, 1961; Albrigo et al., 1965).

B. Molybdenum in Soils

Total soil Mo is generally in the range of 0.5 to 5 ppm (Robinson and Alexander, 1953). Molybdenum deficiency usually occurs because Mo present in the soil is not available, but absolute Mo deficiency can occur on soils formed on sand stones. The quantity and chemical form of Mo in the soil depends upon the soil parent materials and the conditions under which the soil was formed (Gupta and Lipsett, 1981). According to data put together by Bowen (1979) from several sources, Mo output exceeds inputs to a cultivated soil. The largest inputs are from rain and dust, and the largest output is crop removal.

C. Molybdenum Uptake and Translocation

Roots obtain Mo from the soil by interception and Mo ion mass flow through the soil to roots (Barber et at., 1966). Once inside the plant, Mo is translocated, but the form in which it is translocated is unknown. Bukovac and Wittwer (1957) found Mo to be moderately translocatable. Williams (1970) states that Mo is strongly complexed and not mobile in biological systems. However, Kannan and Ramani (1978) found most of the Mo they applied to bean leaves was translocated to the stems and roots. Gupta and Lipsett

(1981) have suggested that because Mo deficiency appears on the whole plant as opposed to only the young parts, Mo must be translocatable. However, because Mo is required to assimilate N, the appearance of deficiency symptoms on the whole plant could have more to do with N translocation than Mo translocation. Wolterbeek and de Bruin (1986) found the polymolybdate ion $Mo_7O_{24}^{-6}$ was quickly transported through the xylem, but once in the leaves Mo was not redistributed within the 24 hour time frame of the experiment. They have suggested that this may explain Bukovac's and Wittwer's (1957) results mentioned earlier. They have further hypothesized that metal-organic compounds are formed in the leaves before redistribution can proceed.

D. Visual Symptoms of Molybdenum Deficiency and Toxicity

Molybdenum is needed by plants in very small quantities. In general, deficiency symptoms occur only on plants with less than a few tenths or hundredths of a ppm in the dry plant tissue (Johnson, 1966; Reuter and Robinson, 1986). On the other hand, a very wide range of concentrations are tolerated (Agarwala and Hewitt, 1954; Joham, 1953; Widdowson, 1966). In fact, it was noted in the first experiment establishing the essentiality of Mo in higher plants, that tomato plants tolerated a wide Mo availability range (Arnon and Stout, 1939). Tomatoes do not show toxicity symptoms until the leaves contain 1,000 to 2,000 ppm Mo. These leaves turned an intense golden yellow

color (Johnson, 1966). A blue pigment is seen in the leaves of cauliflower plants supplied with an excessive amount of Mo (Agarwala, 1950; Warington, 1946), but the blue areas did not contain any more Mo (1,518 to 8,085 ppm) than the normally colored areas (2,852 to 7,455 ppm) (Agarwala and Hewitt, 1954).

Molybdenum deficiency has been studied more thoroughly in cauliflower than in broccoli. Perhaps this is because cauliflower is more likely to show deficiency symptoms than broccoli (Neeman and Goodman, 1954). Broccoli and cauliflower are the same species (*Brassica oleracea*), so they would be expected to respond to and utilize Mo similarly. They do, in fact, develop similar symptoms in response to Mo deficiency. These symptoms include interveinal chlorosis, leaf wrinkling, necrotic leaf edges, whiptail and blindness. Whiptail occurs when the leaf midrib grows, but the leaf lamina growth is reduced. Death of the shoot apex of cauliflower plants, called blindness, causes plants to mature without forming a head (Hewitt and Bolle-Jones, 1952; Hewitt and Jones, 1947; Plant, 1951; Peterson and Purvis, 1961; Waring, 1950).

Stereoscan electron microscopy of Mo deficient cauliflower plants has revealed leaf surfaces with protrusions, perforations and irregular ridges, cytoplasm containing areas of low electron density, and chloroplasts containing grana with only a few compartments and long, thin thylakoids. Enlarged chloroplasts, which may rupture, with

protrusions bounded by the chloroplast and tonoplast membranes seem to be specific to Mo deficiency (Fido et al., 1977).

E. The relationship of molybdenum to nitrogen nutrition

Often Mo deficiency is not easy to distinguish from N deficiency. Although some N-fixing bacteria are able to substitute vanadium for Mo to varying degrees, in general Mo is required for N fixation (Becking, 1962). Molybdenum is a component of nitrogenase. All major N-fixing bacterial groups utilize nitrogenase to reduce N_2 gas to ammonia (Child, 1981). Plants depending on N fixation will therefore actually be N deficient if the N fixing bacteria are Mo deficient.

In addition, Mo is required for nitrate (NO_3^-) metabolism in higher plants because it is part of the active, assimilatory nitrate reductase enzyme complex (Notton and Hewitt, 1977). This enzyme catalyzes the reduction of NO_3^- to nitrite ($NO2^-$). Nitrate reductase will be discussed in more detail in another section.

The only Mo-containing enzyme important to cauliflower appears to be nitrate reductase. Several experiments (Agarwala, 1952; Agarwala and Hewitt, 1955b; Hewitt, 1956) found cauliflower plants grown without NO_3^--N developed whiptail when grown in sand sterilized to prevent nitrification -- conversion of NH_4^+ to NO_3^- -- by bacteria. However, in a more recent experiment, plants provided a NO_3^-

free environment by using a sealed system supplied with filtered air, did not show Mo deficiency symptoms when Mo was not provided. When unfiltered air or NO_3^--N was used, plants showed Mo deficiency symptoms if they were not supplied with Mo (Hewitt and Gundry 1970). It is thought that small amounts of NO_3^- which may have been present in the earlier experiments induced super-oxide production by cytochrome c reductases. The super-oxide then damages chloroplast membranes, leading to whiptail symptoms (Notton, 1983).

Before NO_3^- is assimilated by higher plants, it is converted to NH_4^+ in a two step process. After uptake, NO_3^- is reduced to NO_2^- by nitrate reductase, then NO_2^- is reduced to NH_4^+ by nitrite reductase (Notton, 1983). Assimilatory nitrate reductase is active when both NO_3^- and Mo are present. When NO_3^- is the limiting factor, additional NO_3^- will stimulate nitrate reductase activity after a time lag. When Mo is the limiting factor, additional Mo will immediately increase nitrate reductase activity (Jones et al., 1978)

Several authors report that the rate-limiting step in NO_3^- assimilation is the reduction of NO_3^- to nitrite (Beevers and Hageman, 1969; Guerrero et al., 1981; Notton, 1983). Reisenauer et al. (1982) have suggested that the reason plants tend to grow best with a combination of ammonia and NO_3^- may be because the NO_3^- reducing system is unable to supply the maximum useable level of reduced N.

Davies et al. (1988) concluded that nitrate reductase was probably limiting only during the earliest stages of potato plant growth. Sulfur-deficient rye grass accumulated water soluble organic N (Goh and Kee, 1978), indicating that in this case protein production was limiting. Ullrich (1987) shows data that suggest NO_3^- uptake and nitrate reductase are independently regulated. Ullrich feels that NO_3^- uptake is often what limits N assimilation. Oaks (1986) states that overall NO_3^- assimilation regulation is complex and not at all well understood.

There are, however, many cases where NO_3^- builds up in plant tissue. In these cases, NO_3^- uptake clearly exceeds NO_3^- reduction. For example, low light intensity, drought, or excessive N fertilization encourages NO_3^- accumulation (Goh and Haynes, 1986; van Diest, 1986). Nitrates are known to accumulate in cauliflower plants grown without adequate Mo (Agarwala and Hewitt, 1955a; Hewitt and Jones, 1947).

If there is nitrate reductase activity in broccoli or cauliflower roots, it is probably not significant. Nitrate assimilation site location varies. Xylem sap usually contains a mixture of organic and inorganic N. However, in some species xylem sap N is 95 to 99% NO_3^-, but in other species it is 100% in an organic form. It is assumed that if xylem sap N is in an organic form, NO_3^- was assimilated in the roots. If the xylem sap contains NO_3^- then the roots are not assimilating N and therefore, the above ground portion is assimilating N (Pate, 1973). Rufty et al. (1982)

pointed out that using the ratio of organic N to NO_3^- N in xylem sap to calculate the amount of N assimilated by the roots can greatly over estimate NO_3^- assimilation by roots, because organic N can circulate in the plant by moving from the phloem back into xylem. Routley (1972) has demonstrated that the leaves of certain *Rhododendron* species lack nitrate reductase activity. Dirr (1974) was able to extract nitrate reductase from cranberry roots, but none was found in the leaves. Young stems and fully expanded leaves of cauliflower plants had the greatest net nitrate reductase activity (Hewitt et al., 1955). Shelp (1987b) found that N in broccoli xylem sap was primarily NO_3^--N. Relative nitrate reductase activity at various sites within the plant may vary somewhat among cultivars of the same species (Olday et al., 1976) and with the age of the plant (Oaks et al., 1972; Wallace, 1975; Oaks, 1978). Wallace (1975) found mature roots contain a protein that inactivates nitrate reductase.

F. Molybdenum Applications

1. Methods. It would be of practical value to know when broccoli and cauliflower crops are receiving the amount of Mo needed for maximum yield and the best way to supply the Mo. A wide variety of Mo treatments have been used to correct Mo deficiency of broccoli or cauliflower. Molybdenum application methods include seed treatment (Cheng, 1984; Gupta et al., 1978; Scheffer, 1978; Shepherd,

1962), application to the seedbed (Brandenburg and Buhl, 1955; Jannone, 1964; Morgan and Henderson, 1950; Plant, 1950a; Sauerbeck, 1958; Wilson, 1948), foliar application (Allen, 1967; Robinson and Campbell, 1956; Sauerbeck, 1958; Scheffer, 1978; Turner and McCall, 1957), and field soil application (Brandenburg, 1954, 1961; Brandenburg and Buhl, 1955; Chipman et al., 1970; Dunne and Jones, 1948; Gupta, 1968, 1969; Gupta et al., 1978; Hiraishi and Takeshita, 1966; Jannone, 1964; Jones and Dermott, 1950; Middelburg, 1962; Mitchell, 1945; Morgan and Henderson, 1950; Neeman and Goodman, 1954; Noll, 1955; Plant, 1950b, 1950c, 1951; Polach and Janyska, 1962; Prausse and Gunther, 1968; Robinson and Campbell, 1956; Sagare and Badhe, 1980; Sauerbeck, 1958; Scheffer, 1978; Wilson and Waring, 1948).

Coating cauliflower seeds with sodium molybdate at a rate of 50 or 100% of bare seed weight reduced germination, while a 12.5 or 15% rate only reduced blindness slightly (Scheffer, 1978). In a more recent experiment, Scheffer and Wilson (1987) found there was no significant difference in curd yield between coating the seed at the 50% rate and a 1025 $g \cdot ha^{-1}$ foliar spray. Both treatments increased yield. However, plant establishment was lower for the coated seeds. Noll (1954) reported that applying Mo to the field before transplanting gave better results than watering the plants with a Mo solution after transplanting, because any slowing of plant growth after transplanting increased the severity of whiptail. Wilson and Scheffer (1975) reported that

applying Mo to the seed bed was easier and more effective than a preplant incorporated application to the field, or a foliar spray after symptoms appeared.

2. Timing. It appears that the earlier Mo is applied, the better the plant responds, but seed treatments appear to concentrate too much Mo around the small seeds. Conversely, a soil application of Mo does not cause injury to young seedlings and can remain effective for two or three years (Hiraishi and Takeshita, 1966; Prausse and Gunther, 1968).

3. Sources and amounts. Most researchers have used sodium or ammonium molybdate in their studies, but Middleburg (1962) used a glass frit containing 3% Mo. Cheng (1984) tried several Mo sources and concluded that, based on cauliflower yields, sodium molybdate was the best. Unfortunately, he failed to take into account the wide range of Mo concentrations in the leaves of plants grown with different Mo sources, so it is difficult to evaluate whether the yield differences were due to the form in which the Mo was applied or due to differences in the amount of each material required to provide optimum Mo nutrition. The sodium molybdate treated plants had 23 ppm Mo in the dry leaf matter while ammonium molybdate and phosphomolybdic acid treated plants contained 106 and 300 ppm Mo respectively. Other treatments, including no Mo applied, had tissue levels ranging from 4 to 16 ppm Mo.

The amount of Mo applied ranges widely from 35 grams of Molygrow (38% Mo) (Shepherd, 1962) to 22 kilograms ha^{-1} Mo

(Gupta, 1968). Gupta (1968) did not state the chemical form of Mo used. Common soil applications range from two to five kilograms·ha^{-1} of sodium or ammonium molybdate (Brandenburg and Buhl, 1955; Dunne and Jones, 1948; Neeman and Goodman, 1954; Noll, 1954; Plant, 1950a, 1950b, 1951; Polach and Janyska, 1962, 1965; Prausse and Gunther, 1968; Sauerbeck, 1958; Wilson and Scheffer, 1975). Sagare and Badhe (1980) found 1.5 kg·ha^{-1} Mo produced higher cauliflower yields than 0.75 kg·ha^{-1} Mo. According to Wilson and Scheffer (1975) sodium molybdate at 4.4 kg·ha^{-1} was no more effective than sodium molybdate at 2.2 kg·ha^{-1}. Brandenburg (1961) recommended 4 kg sodium molybdate·ha^{-1} on soils with ironstone deposits or cultivated peat moss, and 1 kg sodium molybdate·ha^{-1} on mineral soils. Chipman et al. (1970) applied eight levels of ammonium molybdate ranging from 0 to 11.2 kg·ha^{-1}. Regression analysis indicated that 1.9 kg·ha^{-1} would give maximum cauliflower yields. Cheng (1984) applied eight levels of sodium molybdate ranging from 0 to 6 kg·ha^{-1}. The highest cauliflower yield was at the 3 kg·ha^{-1} rate.

G. Quantitative Molybdenum Tests

1. Soil analysis. One method of testing for optimum Mo levels is by soil testing. While soil tests may be used as a guide, they are not very accurate. Karimian and Cox (1979) did not find any correlation between cauliflower growth or Mo content and extractable soil Mo determined by

the Grigg method (Grigg, 1953) or by using an anion exchange resin (Bhella and Dawson, 1972) to extract Mo. Soil pH and the active iron ratio was a reasonably good predictor of the relative cauliflower plant response to applied Mo for the 20 Coastal Plain and Piedmont soils they tested.

The pH is a very important factor affecting Mo availability. Molybdenum is more available at a high pH than a low pH. Adsorption in soils is maximum at a pH of 4 (Jones, 1957; Reisenauer et al., 1962). Molybdate can be replaced by the hydroxyl ion (Barrow, 1974). This may explain its increased availability at a high pH. Some low pH soils need liming and a Mo application, while others only require liming to produce a good cauliflower crop (Gupta, 1968, 1969). Although uncommon, the first soils on which higher plants exhibited Mo deficiency in the United States were soils with a pH of 6.3 to 6.8. These soils only require the addition of Mo to prevent the deficiency symptoms (Walker, 1948).

Phosphate and sulfate ions can also have a significant effect on Mo availability. Both phosphate and sulfate can release Mo from the soil (Stout et al., 1951; Barrow, 1974). This should make Mo more available. On the other hand, it has been suggested that phosphate and sulfate may compete with molybdate for uptake (Frausto da Silva and Williams, 1976). This would reduce Mo uptake. Both water (Stout and Meagher, 1948) and soil culture experiments (Stout et al., 1951) have shown that phosphate increases Mo uptake and

sulfate decreases Mo uptake. Bingham and Garber (1960) found that excessive phosphorus fertilization increased Mo uptake in acid soils, but decreased Mo uptake in alkaline soils.

2. Plant tissue analysis. Another way to evaluate whether there is adequate Mo available for maximum yield is by plant tissue analysis. A study found plant tissue analysis was superior to soil sampling for mapping a Mo deposit for subsequent mining (Nature, 1969). However, the tissue concentration necessary for maximum yield is not well defined. Cauliflower plants may appear healthy with less than 1 ppm Mo to over 1,000 ppm Mo in the dry matter (Agarwala and Hewitt, 1954). Even though it has been stated that plant tissues require less than 1 ppm Mo (Stout and Meagher, 1948), for optimum growth, cauliflower and broccoli leaves probably should contain more than 1 ppm Mo for diagnostic purposes. There are a couple of reasons for this.

First, it is difficult to distinguish between plants with adequate and inadequate Mo concentrations when plant tissues contain less than 1 ppm. Gupta et al. (1978) found 0.5 ppm Mo in leaf tissue of cauliflower plants showing deficiency symptoms and 0.3 ppm Mo in the leaves of some plants showing no symptoms. Agarwala and Hewitt (1954) using sand culture and Chipman et al. (1970) using field soil, have shown that over a wide range of low levels of

available Mo, cauliflower tissue Mo concentration changes very little, but there is a large yield increase.

Second, yield studies indicate that maximum cauliflower yield is obtained at tissue concentrations greater than 1 ppm. In sand culture experiments, Singh and Rajput (1976) found 1 ppm Mo in the nutrient solution gave the highest cauliflower yield. Agarwala (1950) found yield increases continued with up to 5 ppm in the nutrient solution. Tissue concentrations were not measured in these two experiments, but were probably quite high. Agarwala and Hewitt (1954) found marked increases in cauliflower dry weight yields when up to .0005 ppm Mo with 6 meq. $NO3^-$, and up to 0.005 ppm Mo with 24 meq. NO_3^- was used in the nutrient solution. This corresponded to 0.27 and 0.93 ppm Mo respectively in the dry matter of leaves harvested 65 days after planting. In contrast to dry weight yield, fresh weight yield was significantly higher, with 0.48 ppm than with 0.005 ppm Mo in the nutrient solution. At 65 days the leaf dry matter Mo content was 36.4 ppm with 6 meq. NO_3^- and 74.2 ppm with 24 meq. NO_3^-. In an auxiliary experiment 9.6, 19.2, 38.4, and 76.8 ppm solution Mo with 9.2, or 29.5 meq. NO_3^- was used to observe the response to excessive levels. The highest yield was with 19.2 ppm Mo and 29.5 meq. NO_3^-. The leaf dry matter contained 566.8 ppm Mo. Two experiments using field soil have also been done. Using regression analysis, Chipman et al. (1970) calculated the optimum Mo leaf tissue concentrations to be 2.13 ppm for 'Snowball', and 1.22 ppm

for 'Pioneer'. Cheng (1984) reported maximum cauliflower yields when the Mo tissue concentration was 94 ppm.

3. Others. Two other methods of determining whether or not a crop has an adequate Mo supply have been used. Because Mo deficient plants accumulate NO_3^-, Plant (1951) determined the NO_3^- content of broccoli and cauliflower plants with and without whiptail symptoms and found this test was an unsatisfactory method of detecting Mo deficiency. It has also been suggested that infiltrating leaf fragments with a Mo solution and measuring the rise, if any, in nitrate reductase activity, might show whether or not a plant was receiving an adequate Mo supply (Shaked and Bar-Akiva, 1967). The validity of this method for determining broccoli or cauliflower Mo has not been established.

III. ADJUVANTS AND FOLIAR NUTRITION

A. Introduction

Nutrient salts, such as sodium molybdate (Na_2MoO_4) are polar. Polar solutes will dissolve in polar solvents such as water. The surfaces of leaves are non-polar and can be dissolved in non-polar solvents, but they repel water. The active part of a surfactant has a polar and a non-polar functional group, which allows water containing salts such as Na_2MoO_4 to make contact with the leaf surface. The polar group is called hydrophilic and the non polar group is

called lipophilic. This hydrophilic-lipophilic portion is the active part.

Surfactants are classified based on the active part. There are four major groups. The active part of a non-ionic surfactant has no ionizable polar functional groups; instead it is composed of chains of hydrophilic and lipophilic segments. The active part of an anionic surfactant has a negative charge, the active part of a cationic surfactant has a positive charge, and an ampholytic surfactant has areas of both positive and negative charge (van Valkenburg, 1982).

Adjuvants are added to spray mixtures to increase foliar uptake of chemicals such as nutrients, growth regulators, and herbicides. When chemicals are applied to foliage, uptake generally declines exponentially (Price and Anderson, 1985). The enhancement or suppression of uptake depends on the interaction of the plant surface, the chemical being applied, and the adjuvant (Freed and Montgomery, 1958; Jansen, 1964).

It is difficult to predict or control the amount of chemical applied to foliage that will be taken up by a plant, because uptake is governed by numerous factors. These factors can influence foliar uptake of chemicals greatly. For example, the uptake of glyphosate, a water soluble herbicide, sometimes proceeds slowly, taking several days (Schultz and Burnside, 1980). At other times over half of the herbicide is absorbed within 4 hr (Sprankle et al.,

1975). Similarly, the response to foliar fertilization is often inconsistent (Neumann, 1982).

Polar, water soluble salts apparently pass through the cuticle via polar pathways that are permeable to water and small solute molecules (Franke, 1967; Haas and Schönherr, 1979; Hoch, 1979; Schönherr and Bukovac, 1970). McFarlane and Berry (1974) measured the penetration rate of several cations through isolated leaf cuticles. They found that the smaller the ionic radius was, the faster the ion penetrated the cuticle. Calcium, which has a relatively large ionic radius, penetrated the cuticle slowly.

B. Wetting

Surfactants are used to increase absorption by thoroughly wetting plant surfaces (Sands and Bachelard, 1973). The cuticles of *Brassica* spp. are covered with a relatively thick epicuticular wax which has a unique chemistry and, perhaps related to its chemistry, a unique morphology (Baker, 1982). This wax repels polar molecules such as water.

When no surfactant is used, water beads and rolls off cauliflower and broccoli leaf surfaces. Stevens and Baker (1987) found rape leaves (*Brassica napus*) were especially hard to wet and surfactants increased the uptake of several herbicides by facilitating leaf surface wetting. Stevens et al. (1988) found adding a surfactant had a variable effect on the uptake of polar and nonpolar compounds, but

surfactants always increased uptake by waxy species (rape and strawberry). Cantliffe and Wilcox (1972) found cabbage leaves only absorbed manganese (Mn) when a surfactant was used, or the formation of surface wax was inhibited by ethyl N,N-dipropylthiolcarbamate (EPTC).

As the surface tension of a solution decreases the contact angle between the solution and the leaf surface generally decreases. Contact angle is a measure of the wetting ability of a solution. A small contact angle indicates thorough wetting. Stevens and Bukovac (1987a) found the surface tension of octylphenoxy surfactants increased with their hydrophile:lipophile balance (HLB). They also found some surfactants wetted a larger area than would have been expected from the measured contact angle. These surfactants were relatively lipophilic. Bukovac (1987a) suggested that these surfactants probably wetted a larger area of the leaf because of their attraction for the leaf surface.

Organosilicone surfactants are especially effective wetters. Solution surface tensions below 30 dynes cm^{-1} are possible without phytotoxicity (Neumann and Prinz, 1974b). Field and Bishop (1988) reported that Silwet L-77 increased the uptake rate of glyphosate, a water soluble herbicide; however, it did not increase total uptake if the herbicide was washed off before it was completely absorbed (Field and Bishop, 1988).

Silwet L-77 is currently one of the more common organosilicone surfactants. Silwet L-77 is an effective, relatively non-phytotoxic surfactant for treating iron chlorosis of citrus trees (Neumann and Prinz, 1974a). Silwet L-77 increases Ca uptake into apple fruit (Lee and Dewey, 1981), and increases bean leaf absorption of iron and phosphate (Neumann and Prinz, 1974b). When ^{15}N labeled potassium nitrate was applied to prune leaves, Silwet L-77 doubled initial uptake of NO_3^- (Leece and Dirou, 1977).

Leece and Dirou (1979) have discused the drawbacks of using surfactants such as Silwet L-77. They can increase runoff, thus reducing the volume of solution deposited on the leaf. The thin film left on plant surfaces dries rapidly. Because the leaves are wet so thoroughly, applied chemicals are absorbed rapidly, increasing the chance of injury. Occasionally, Silwet L-77 may injure leaves. In one case, a 0.05% (v/v) Silwet L-77 solution produced severe bean leaf curl (Neumann and Prinz, 1975).

C. Retention

Increasing the amount of material retained on the plant surface can increase uptake. The angle of the leaf affects spray retention. Horizontal leaves retain the most spray (Ennis et al., 1952). This could be a very important consideration when applying chemicals to young broccoli or cauliflower leaves because these leaves are in a vertical or nearly vertical position. On the other hand young leaves

tend to take up chemicals more easily than mature leaves (King and Radosevich, 1979; Leon and Bukovac, 1978).

Spray retention can be increased through the use of polymeric stickers (Hull, 1970) and smaller spray droplets (Blackman et al., 1958). However, according to Hull (1970), the results are variable when polymeric stickers are added.

D. Drying Time

The amount of time it takes for the solution to dry on the plant surface affects uptake. Drying time is affected by environmental conditions and spray solution composition. Stevens et al. (1988) found that although the rate of uptake was 100 to 1000 times greater during droplet drying than from dry deposits, total uptake during droplet drying was small because drying occurs over a short time period. This indicates that drying time is not of prime importance. However, many experiments have shown that the drying rate is important. These experiments show that there is a drying time, which is neither the longest or shortest time period tested, at which maximum uptake occurs (Allen, 1970; Bukovac and Wittwer, 1957; Greene and Bukovac, 1971; Lidster et al., 1977; Reed and Tukey, 1978; Stevens and Bukovac, 1987b; van Goor, 1973).

Certain adjuvants, such as hygroscopic chemicals, oils, and humectants (Hull, 1970), and high relative humidity (RH) can increase drying time. Some surfactants not only increase uptake due to their wetting ability, but also

because they are hygroscopic (Anderson and Girling, 1983; Stevens and Bukovac, 1987b). Stevens and Bukovac (1987b) found 2D-glucose uptake, which is very water soluble, was enhanced at high RH. However, when a hygroscopic surfactant was used, high RH decreased initial (1.5 hr) uptake. They suggested that hygroscopic surfactants may have diluted the solution. When apples were stored at 90 to 95+% RH after the apples were dipped in $CaCl_2$ solution, the uptake of Ca was sometimes reduced when the RH was above 95% (Betts and Bramblage, 1977). Lidster et al. (1977) found Ca uptake by dipped apples was reduced by very high and very low storage RH. According to van Goor (1973) RH affects the uptake of Ca by affecting the drying time.

E. Chemical Form

The form in which nutrients are applied has a significant effect on nutrient uptake. Glenn and Poovaiah (1985) measured the rate of Ca uptake from $CaCl_2$, calcium acetate ($Ca(C_2H_3O_2)_2$), calcium nitrate ($Ca(NO_3)_2$), and two commercial Ca formulations. Of the forms tested, $CaCl_2$ penetrated the cuticle the fastest. They also found $CaCl_2$ dried slower than the other forms of Ca used. This is not surprising, because $CaCl_2$ is so hygroscopic that it liquifies when exposed to humid air.

Reed and Tukey (1978) found sodium phosphate and potassium phosphate uptake was dependant on the pH of the solution applied. Ammonium phosphate was readily absorbed

at any pH, while calcium phosphate was not readily absorbed at any pH.

Because the cuticle is a barrier to polar compounds, uptake of similar compounds increases as the lipophilicity of the compounds increases (Norris and Freed, 1966; Sargent et al., 1969) Lipophilic compounds such as 2,4-D are absorbed by the cuticle (Stevens and Baker, 1987), and therefore, surfactants may not increase their uptake. In fact, Stevens and Baker (1987) found as wetting increased, 2,4-D uptake decreased. Lipophilic compounds may also dissolve surface waxes (Bukovac et al., 1983).

F. Growing Conditions

Baker (1974) found growing conditions affect Brussels sprout (*Brassica oleracea* var. *gemmifera*) wax morphology, chemistry, and thickness. A change in chemistry was only noticeable under widely differing environmental conditions. In general, as evidenced from wax yields, wax production increases as radiant energy increases and temperature and humidity decrease. An increase in radiant energy rate increased the size and number of crystalline wax forms. An increase in temperature resulted in a more horizontal rather than vertical crystalline growth habit. An increase in RH decreased the density of tubular waxes formed on plants grown at 15°C, and restricted the development of dendrites (branching wax forms) on plants grown at 32°C. Changes in

wax morphology were visible within 48 hours of the change in ambient conditions.

Reed and Tukey (1982) grew Brussels sprouts at 15°C and 25°C. Rubidium (Rb^+) phosphate ($H_2PO_4^-/HPO_4^{-2}$) penetrated isolated cuticles from plants grown at 15°C faster than the cuticles of plants grown at 25°C.

Hunt and Baker (1982) have shown that soil moisture content also affects leaf wax deposition. Wax deposits on pea (*Pisum sativum*) leaves not only increased as irradiance increased and humidity decreased, but also as soil moisture decreased. As wax deposits increased, the uptake of 1-naphthylacetic acid (NAA) decreased.

G. pH

The pH of the spray solution is important, but the optimum pH and magnitude of its effect varies with the nutrient applied. The retention of $^{45}CaCl_2$ in apple fruit cuticles increases as pH increases (Chamel, 1983). Glenn and Poovaiah (1985) found $CaCl_2$ penetration of apple fruit cuticles was greater at pH 3 than pH 11. They found pCa -- Log_{10} free Ca^{2+} -- was also higher at pH 3 than pH 11, indicating that an increase in pH may increase Ca uptake by increasing the availability of Ca^{+2} ions. Cherry fruit took up more Ca when the dipping solution was pH 7, but when the dip was pH 4 there was a greater reduction of pitting than when the pH was 7 (Lidster et al., 1979). McFarlane and Berry (1974) noted a five fold increase in the rate of K

movement through cuticles under basic vs. acidic conditions. Reed and Tukey (1978) studied the uptake of phosphorus by chrysanthemum leaves. They found maximum uptake was at pH 3 to 6 with sodium phosphate and pH 7 to 10 with potassium phosphate. The most dramatic increase in uptake was associated with necrotic leaf spots that occurred at pH 2.

H. Temperature

Temperature may also affect uptake. Glenn and Poovaiah (1985) measured the rate of Ca penetration through apple cuticles. They found as the temperature decreased the rate of Ca penetration also decreased. Lee and Dewey (1981) increased the infiltration of Ca by decreasing the temperature of the dip solution and increasing the temperature of the apple.

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Chapter 2

CALCIUM APPLICATIONS REDUCE TIPBURN IN CAULIFLOWER

I. ABSTRACT

If cauliflower (*Brassica oleracea* var. *botrytis*) plants are grown in a substrate containing insufficient calcium (Ca), tipburn will develop on rapidly growing leaves. When tipburn is substantial, the poor leaf cover results in discolored cauliflower. Soft rot may develop in the necrotic leaf tips, spreading to adjacent curds.

In the greenhouse, cauliflower developed substantial tipburn when grown in a modified Hoagland's solution containing 0.5 mM Ca. With 2.0 or 8.0 mM Ca there was almost no tipburn.

In an initial field experiment, there was significantly less tipburn when foliar Ca was applied. In subsequent field experiments, cauliflower was treated with 340 or 1000 $kg \cdot ha^{-1}$ Ca as $CaCl_2$ or calcium sulfate ($CaSO_4$) preplant incorporated (ppi); or side-dressed twice with 170 $kg \cdot ha^{-1}$ Ca as $CaCl_2$ or $CaSO_4$; or sprayed with 3.6 $kg \cdot ha^{-1}$ Ca as 5 or 6 weekly foliar $CaCl_2$ applications, beginning 7 weeks after transplanting. Soil Ca applications resulted in greater Ca concentrations in leaves and curds. In the experiment with the greatest incidence of tipburn, there was significantly less tipburn in plots receiving 1000 $kg \cdot ha^{-1}$ Ca as $CaCl_2$ or foliar-applied $CaCl_2$. Tipburn decreased with increasing

extractable soil Ca, but tipburn increased as curd Ca increased. As Ca curd increased, there was less Ca in the surrounding leaves.

II. INTRODUCTION

Tipburn can be a serious problem in cauliflower production. Tipburn usually occurs on young leaf tissue during a period beginning just prior to curd development. When tipburn is severe, the wrapper leaves are not large enough to cover the curd, and the curd may become discolored by sunlight. The tipburned leaves may also cause discoloration or rotting of the curd as a result of soft rot infection.

In a greenhouse experiment, Maynard et al. (1981) found that when Ca was relatively low (1 meq·liter^{-1}) tipburn was common. They suggested that foliar applications of Ca might prevent tipburn in the field. They did not recommend applying Ca to the soil because some leaves on their greenhouse-grown plants exhibited tipburn even with a seemingly adequate supply of Ca in the soil.

Recently Rosen et al. (1987) tried to prevent cauliflower tipburn through $CaSO_4$ applications to field soil, but were unsuccessful.

Greenhouse and field experiments were performed to develop methodology to prevent tipburn in cauliflower through soil and foliar applications of Ca.

III. MATERIALS AND METHODS

A. Introduction

Experiments were conducted in the Plant Science Greenhouse and in the field at the Horticultural Research Center, Michigan State University, East Lansing, Michigan to evaluate the effects of Ca availability on the incidence and severity of tipburn. 'White Fox' cauliflower was used in all experiments. Materials and methods common to all field experiments are described under general field practices. Materials and methods applicable to all Ca experiment are described in the sections on tissue and statistical analysis. Additional information is presented under individual experiments.

B. General Field Practices

Fields to be planted with cauliflower were broadcast with 45 $kg \cdot ha^{-1}$ nitrogen (N), 40 $kg \cdot ha^{-1}$ phosphorus (P), and 75 $kg \cdot ha^{-1}$ potassium (K) and then plowed. Before transplanting 700 $g \cdot ha^{-1}$ trifluralin, 56 $kg \cdot ha^{-1}$ N, and 4.6 $kg \cdot ha^{-1}$ boron (B) were disked in. At transplanting, 240 ml of a starter solution containing 0.95 $ml \cdot liter^{-1}$ chlorpyrifos and 35 $g \cdot liter^{-1}$ 10N-23P-14K fertilizer was applied to each plant as it was set in the soil. The plants were set with a single row mechanical transplanter.

The plants were sidedressed with 56 $kg \cdot ha^{-1}$ N (165 $kg \cdot ha^{-1}$ NH_4NO_3) 3 and 7 weeks after transplanting. The plots were single rows 9.1 m long by 1.2 m wide with guard rows between treatment rows. Plants were set 50 cm apart in the row. The transplants were grown in 96-cell flats at the Plant Science Greenhouse. These cells are 5.5 cm by 4 cm at the top and 4 cm high. The cells held appoximately 30 cc of media.

Foliar treatments were applied with a hand carried, carbon dioxide (CO_2) powered sprayer at a pressure of 200 kPa. The spray volume used in 1985 was 190 $liter \cdot ha^{-1}$, but was increased to 370 $liter \cdot ha^{-1}$ in 1986. A 9508E spray tip was used in 1985 and 1986. In 1987 and 1988 a TJ60-8006E spray tip was used to provide better coverage. This spray tip has dual orifices and produces smaller droplets. A nonionic surfactant was added to the tank mixes. The surfactants used were Triton AG-98 0.5% (v/v) in 1985 and 0.1% (v/v) in 1986, and Silwet L-77 0.075% (v/v) in 1987 and 1988. Molybdenum was applied as $Na_2MoO_4 \cdot 2H_2O$. Calcium was applied as $CaCl_2$ in foliar sprays, and $CaCl_2$ or $CaSO_4$ in soil applications.

C. Tissue analysis

Unless otherwise noted, at least six curd pieces or six leaves collected from separate plants in each plot were combined to form one sample for mineral analysis. Samples were not taken from plants at the ends of the rows and from

plants that did not appear to be true to type, such as those with an unusual leaf shape or a green curd. After harvest, tissue samples were dipped 6 to 8 times in 0.15 N hydrochloric acid (HCl) and shaken to remove excess water. Then this rinsing method was repeated twice in separate containers of deionized water. The washing process takes less than a minute. The samples were forced air dried at 70°C and ground in a Wiley mill to pass through a 1.3 mm screen. The ground tissue was redried at 70°C for at least 24 hours and weighed for ashing.

Tissue samples from 1985 and 1986 were dry ashed. The tissue was weighed into Coors porcelain crucibles and ashed at 550°C for 8 hours in a muffle furnace. The ashed tissue was then dissolved in 10 ml of 1.5 N HCl. The samples were rinsed out of the crucibles and brought up to volume with 1.5 N HCl. Prior to analysis, the samples were filtered through Schleicer & Schuell number 588 analytical filter paper. Lanthanum was added, as described below, to samples prepared for Ca analysis.

In 1987 and 1988, Ca samples were prepared by digesting 0.1 g of tissue in 0.5 ml of 30% hydrogen peroxide (H_2O_2) and 1 ml of perchloric acid ($HClO_4$) for 5 min on a Tecator Digestion System 40, 1016 digester at 300°C. The 100 ml digestion tubes were then removed from the digestion block and 1 ml of 30% H_2O_2 was added to each sample. Then the digestion tubes were returned to the 300°C digestion block for 30 to 45 min. After the digestion tubes were filled

one-half to three-quarters full with deionized water, the samples were reheated slightly to dissolve crystals that form when the samples cool. The digestion procedure described above was adapted from Adler and Wilcox (1985).

Five percent weight for volume ($g \cdot ml^{-1}$) lanthanum (La) was added to equalize ionization among the samples and standards. Lanthanum also acts as a releasing agent, preventing the formation of Ca compounds which are not atomized by a C_2H_2 flame. The La stock solution contained 180 ml of concentrated $HCl \cdot liter^{-1}$ and 117 g of $La_2O_3 \cdot liter^{-1}$. It was prepared by mixing lanthanum oxide (La_2O_3) with a small amount of deionized water and adding HCl to dissolve the La_2O_3 before bringing the solution to volume with deionized water.

The samples were analyzed with an Instrumentation Laboratory Video 12 atomic absorption - atomic emission spectrophotometer. Calcium was analyzed at a wavelength of 422.7 nm and a bandwidth of 1.0 nm by acetylene (C_2H_2) flame, atomic absorption spectrophotometry with an Instrumentation Laboratory hollow cathode-Ca lamp. Molybdenum was analyzed at a wavelength of 313.3 nm and a bandwidth of 0.5 nm by nitrous oxide-acetylene (NO_2-C_2H_2) flame, atomic absorption spectrophotometry with an Instrumentation Laboratory hollow cathode-Mo lamp. All samples were aspirated at a 6 $ml \cdot min^{-1}$ flow rate.

D. Statistical Analysis

An analysis of variance was done on all experiments. LSD values were computed for the relevant levels of significance. Statistical analyses were performed using MSTAT and PlotIt. Correlation or regression analyses were computed when appropriate.

E. Greenhouse Experiments

1. Experiment one: Effect of Ca on tipburn and curd quality under poor environmental control (1985).
Cauliflower seeds were planted 9 June 1985 in 72-cell flats filled with vermiculite. These cells were 5.5 cm wide at the top, 4 cm high, and hold about 45 cc of media. The seedlings were watered with tap water and fertilized with 2.4 $g \cdot liter^{-1}$ of a soluble 20N-8.7P-17K fertilizer. For the remainder of the experiment, all solutions were made with deionized water and reagent grade chemicals.

On 14 July, the plant roots were washed with deionized water to remove the vermiculite, and individual seedlings were planted in pots which were 22 cm tall and 25 cm in diameter at the top (2 gallon pots). The pots were filled with about 8,000 cc of coarse silica sand that had been washed with 10% (v/v) HNO_3 followed by deionized water.

The plants were fertilized with an automatic drip irrigation system applying about 500 ml of a complete nutrient solution every 8 hours. For the first four weeks all plants received the same nutrient solution (Table 1).

The Ca treatments (Table 2) began on 13 August and continued until curd harvest.

The plants were arranged on a greenhouse bench in a completely randomized design. Each treatment had 20 single plant replicates.

The plants were grown under natural light, providing about 14 $mol \cdot m^{-2} \cdot day^{-1}$ photosynthetic photon flux (PPF) and maintained at a maximum daily temperature of 26°C. On 28 August, the electrical system failed and the greenhouse temperature rose to 40°C. The experiment was moved to another greenhouse with cooling fans but no precise temperature control. The temperature was irregular for the rest of the experiment.

Recently expanded leaves were harvested from each plant on 26 August and 30 September for Ca analysis. Some plants were so severely tipburned that no leaf sample could be harvested from them on 30 September

Heads and shoots of all plants were weighed on 8 October. The shoot weight included the entire above ground portion of the plant excluding the curd.

Tipburn and curd breakdown were rated at harvest. Tipburn was rated on a scale of 1 to 5: 1 = no tipburn; 5 = most of the leaves tipburned. Curd breakdown begins with water soaked areas which turn brown and are invaded by secondary pathogens. Curd breakdown was rated 1 to 5: 1 = no breakdown; 2 = water-soaked areas; 3 = large water-soaked or small brown areas; 4 = some rotting; 5= much rotting.

Table 1. Nutrient salts included in the solution applied to greenhouse experiments 1 and 2 before the Ca treatments began.

Compound[z]	Concentration
$MgSO_4 \cdot 7H_2O$	1.0 mM
$NaH_2PO_4 \cdot H_2O$	1.0 mM
$Ca(NO_3)_2 \cdot 4H_2O$	2.0 mM
KNO_3	3.0 mM
$CuSO_4 \cdot 5H_2O$	0.50 μM
$MnSO_4 \cdot H_2O$	2.0 μM
$ZnSO_4 \cdot 7H_2O$	2.0 μM
H_3BO_3	25 μM
KCl	50 μM
Fe - DTPA[y]	110 μM

[z]NaOH added to bring the pH up to 5.7.

[y]Fe - DTPA = Sodium ferric diethylenetriamine pentaacetate.

Table 2. Nutrient salts included in the treatment solutions applied to greenhouse experiments 1 and 2.

Compound[z]	Concentration
$Ca(NO_3)_2 \cdot 4H_2O$	0.50 mM
$CaCl_2$[y]	1.5 mM
$CaCl_2$[x]	7.5 mM
$Mg(NO_3)_2 \cdot 6H_2O$	0.50 mM
$MgSO_4 \cdot 7H_2O$	0.50 mM
$NaH_2PO_4 \cdot H_2O$	1.0 mM
NH_4NO_3	2.0 mM
KNO_3	3.0 mM
$CuSO_4 \cdot 5H_2O$	0.50 μM
$MnSO_4 \cdot H_2O$	2.0 μM
$ZnSO_4 \cdot 7H_2O$	2.0 μM
H_3BO_3	25 μM
KCl	50 μM
Fe - DTPA[w]	110 μM

[z]NaOH added to bring the pH to 5.7.

[y]Added to make the 2.0 mM Ca solution.

[x]Added to make the 8.0 mM Ca solution.

[w]Fe - DTPA = Sodium ferric diethylenetriamine pentaacetate.

2. Experiment Two: Effect of Ca on Tipburn and curd quality under good environmental control (1986). The preceding experiment was repeated. However, the seedlings were watered with nutrient solution once a week (Table 1) and with deionized water when necessary.

Seeds were planted on 9 January 1986 and the seedlings were transplanted on 6 March. Calcium treatments began 7 April.

The greenhouse temperature was maintained at 22 to 26°C. The plants were grown under natural light which provided about 8 $mol \cdot m^{-2} \cdot day^{-1}$ PPF.

A recently expanded leaf was harvested from each plant on 24 April and 27 May and a few small leaves surrounding the curd (curd leaves) were harvested on 27 May for Ca analysis. The plants were evaluated for tipburn and curd breakdown, shape and quality on 20 May. The plants were harvested and fresh weights of the curds and the above ground portions, excluding the curds, were recorded on 27 May.

Curd color ranged from white to somewhat yellow. The color of the curds did not seem to be directly related to the amount of sunlight the curds received, because plants with good wrapper leaf growth and possibly more shading of the curds from the sun were not consistently white. The curds were rated on a 1 to 5 scale: 1 = white; 5 = yellow.

Curd shape was rated on a 1 to 5 scale: 1 = smooth, round; 5 = rough, irregular.

Curd quality was based on the overall appearance of the curd: 1 = excellent; 2 = slight imperfections; 3 = useable; 4 = unusable; 5 = substantially decomposed. Curds rated 1 or 2 are marketable curds. A curd rated 3 would probably not be marketable after shipment.

F. Field Experiments

1. Experiment one: Irrigation with Mo and Ca applications (1985). Cauliflower seeds were planted 9 June 1985 and the seedlings were transplanted into the field on 8 July. The soil was a Capac loam with 2% organic matter, a pH of 6.8, and a cation exchange capacity of 9 meq. Calcium contributed 71% of the exchangeable bases.

The experiment was designed as a split plot with irrigation as main plots, and with three Ca and four Mo treatments arranged factorially as subplots.

The entire experiment was irrigated immediately after transplanting. No additional irrigation was applied to the unirrigated plots. There was sufficient rain during the experiment that non-irrigated plots suffered little moisture stress (Appendix).

Irrigation treatments were:

1. No irrigation
2. Irrigated 25 $mm \cdot week^{-1}$.

Molybdenum treatments were :

1. No Mo added
2. 5 $kg \cdot ha^{-1}$ Mo soil strip application at plant bases after transplanting
3. 210 $g \cdot ha^{-1}$ Mo foliar sprays (4)
4. Seeds dipped in a 2 M Mo solution.

Calcium treatments were:

1. No Ca added
2. 1.7 $kg \cdot ha^{-1}$ Ca foliar sprays (5)
3. 3.4 $kg \cdot ha^{-1}$ Ca foliar sprays (5).

The Mo strip was applied on 8 August. The foliar treatments were applied on 8 and 23 August and 5 and 19 September. Foliar Ca treatments were applied on 23 and 29 August and 5, 12, and 19 September.

From 20 September to 2 October, the curds were harvested as they matured, weighed, and evaluated for hollow stem, tipburn, and curd quality. Leaf samples, consisting of 3 to 5 recently expanded leaves from each plot, were taken on 8 August and 9 September.

2. Experiment two: Irrigation with Mo and Ca applications (1986). Cauliflower was seeded 4 June and transplanted 7 July. The field soil was a Marlette fine sandy loam with 2% organic matter, a pH of 6.8, and an exchange capacity of 4 meq. Calcium was 57% of exchangeable bases.

The experiment was a split plot with two irrigation levels as main plots, and with five Ca and two Mo levels arranged factorially as subplots.

The entire experiment was irrigated immediately after planting. No additional irrigation was applied to the unirrigated plots, and 25 mm of irrigation was applied to irrigated plots if natural precipitation was less than 25 mm for the preceding week.

Irrigation treatments were:

1. No irrigation
2. 25 mm of irrigation applied if natural precipitation was below 25 mm the preceding week.

Molybdenum treatments were:

1. No Mo added
2. 280 $g \cdot ha^{-1}$ Mo foliar sprays (11)
3. 4.4 $kg \cdot ha^{-1}$ Mo soil strip application at plant bases on 9 July.

Calcium treatments were:

1. No Ca added
2. 4.0 $kg \cdot ha^{-1}$ Ca (11 $kg \cdot ha^{-1} CaCl_2$) foliar sprays (11)
3. 28 $kg \cdot ha^{-1}$ Ca sidedresses (80 $kg \cdot ha^{-1}$ $CaCl_2$) (2)
4. 56 $kg \cdot ha^{-1}$ Ca sidedresses (160 $kg \cdot ha^{-1}$ $CaCl_2$) (2)
5. 56 $kg \cdot ha^{-1}$ Ca sidedresses (295 $kg \cdot ha^{-1}$ $Ca(NO_3)_2$) (2)

The $Ca(NO_3)_2$ treatment also supplied 46 $kg \cdot ha^{-1}$ N, so 134 $kg \cdot ha^{-1}$ NH_4NO_3 was applied to the other treatments to supply 46 $kg \cdot ha^{-1}$ N. The sidedresses were applied 24 July and 13 August. The foliar treatment was applied in 11 weekly sprays beginning 9 July. and ending 18 September

Leaves were harvested for Ca and Mo analysis. Recently expanded leaves were harvested on 7 August and 8 Sept., and curd leaves were harvested on 28 September. The curds were harvested and weighed in mass per plot as they matured from 17 to 28 September.

3. Experiment three: Soil and foliar Ca applications to control cauliflower tipburn (Spring 1987). Cauliflower was seeded 24 April 1987 and transplanted into a field of Marlette sandy loam soil on 20 May. This soil had a pH of 5.4, a cation exchange capacity of 7 me·100 g^{-1}, and 2% organic matter. Calcium provided 74% of the bases.

The treatments are listed in Table 3. The preplant incorporated (ppi) treatments were incorporated 10 to 15 cm deep with a rototiller before transplanting. All rows were rototilled to prepare similar planting conditions for all treatments. The Ca sidedress treatments were applied on 17 June and 8 July. The foliar sprays were applied on 8, 15, 23 and 29 July and 5 August.

The experiment was irrigated with 25 mm of water after transplanting to obtain a good stand, and throughout the trial to supply at least 25 mm of moisture each week.

A recently expanded leaf was harvested from each plant for Ca analysis on 19 June and 19 July. The curd and curd leaves were harvested on 4 August. The curd samples consisted of one or two small pieces per plant broken off the edge of the curd. The number of tipburned leaves per plant was counted on 30 July. The plants at the ends of

each plot were not included in the count. The curds were harvested as they matured from 28 July to 18 August. The weight of the curds and the above ground portion of the plants was recorded.

Soil samples were collected on 24 August by taking twenty, 20-cm deep soil cores from each plot. The soil samples were mixed, air dried, ground in a flail grinder, and passed through a 2.5 mm screen. The soil samples were analyzed at the Michigan State University Soils Laboratory, using methods adapted from "Recommended Chemical Soil Tests Procedures for the North Central Region" (1988). Soil pH was determined using a 1:1 (v/v) slurry of deionized water and soil. Extractable Ca was determined using 2 g of soil in 20 ml of neutral, 1 N ammonium acetate ($NH_4C_2H_3O_2$) shaken for 5 min at 180 oscillations per min. Soil extracts were filtered through Whatman number 2 filter paper.

The Ca content of the soil extracts was determined by the same method used for tissue samples. The standards used for soil extracts contained 1 N $NH_4C_2H_3O_2$ in addition to La.

Table 3. Treatments applied to field experiments 3, 4, and 5.

1. Control
2. 340 kg·ha^{-1} Ca (1040 kg·ha^{-1} $CaCl_2$) ppi
3. 340 kg·ha^{-1} Ca (1490 kg·ha^{-1} $CaSO_4$) ppi
4. 1000 kg·ha^{-1} Ca (3110 kg·ha^{-1} $CaCl_2$) ppi
5. 1000 kg·ha^{-1} Ca (4460 kg·ha^{-1} $CaSO_4$) ppi
6. 170 kg·ha^{-1} Ca (519 kg·ha^{-1} $CaCl_2$) sidedresses (2)
7. 170 kg·ha^{-1} Ca (743 kg·ha^{-1} $CaSO_4$) sidedresses (2)
8. 3.6 kg·ha^{-1} Ca (11 kg·ha^{-1} $CaCl_2$) foliar spray (5 or 6)

4. Experiment four: Soil and foliar Ca applications to control tipburn of cauliflower (Fall 1987). The preceding experiment was repeated. Cauliflower seeds were planted 31 May 1987 and transplanted into a field of Marlette sandy loam and Capac loam on 29 June. The soil had a pH of 5.2, a cation exchange capacity of 11 me·100 g, and 2.5% organic matter. Calcium provided 68% of the bases.

The Ca sidedresses were applied on 30 July and 25 August. Foliar treatments were applied on 19 and 28 August and 3, 11, 17, and 24 September.

Recently expanded leaves were harvested on 30 July and 28 August. Curd leaf and curd samples were harvested on 21

September. The tipburned leaves on each plant were counted on 21 September. The curds and remaining plant shoots were harvested and weighed as they matured from 25 September to 6 October. Soil samples were taken on 6 October.

5. Experiment five: Soil and foliar Ca applications to control cauliflower tipburn (1988). The preceding experiment was repeated. Cauliflower seeds were planted on 22 April and transplanted into a field of Capac loam on 23 May. The soil had a pH of 6.2, a cation exchange capacity of 10 me·100 g, and 3% organic matter. Calcium provided 71% of the bases.

The Ca sidedresses were applied on 26 June and 22 July. Foliar treatments were applied on 3, 10, 18, and 26 July and 3 August.

Recently expanded leaves were harvested on 22 June and 22 July. The number of tipburned leaves per plant was recorded on 31 July and again as each curd was harvested. Because the plants matured unevenly, the curd leaf and curd samples were harvested from each plot on different dates. The samples were harvested when the most curds were harvested. Harvest commenced 1 August and was completed 17 August. The weight and quality of the curds were recorded. Soil samples were collected on 26 August.

6. Experiments three, four, and five: Combined data excluding foliar treatments (1987-1988). Data from field experiments during 1987 and 1988 were combined to test for significant correlations. Data for foliar-applied

treatments were not included in the correlations, because a direct Ca application should not depend on soil Ca levels or translocation. For the correlation between the concentration of Ca in the soil and recently expanded leaves harvested 30 day after transplanting, sidedressed treatments were not included either, because the sidedressed had not been applied at 30 days and the soil samples were taken after harvest.

IV. RESULTS

A. Greenhouse Experiments

1. Experiment one: Effect of Ca on tipburn and curd quality under poor environmental control (1985). Curd breakdown was more severe at the 0.5 mM Ca level, with essentially no curd breakdown at the 2.0 and 8.0 mM Ca levels (Table 4). The average Ca concentration in recently expanded leaves was below 1% when the substrate Ca concentration was 0.5 mM, and 2% or above when the substrate Ca concentration was 2.0 or 8.0 mM (Table 5). The 2.0 mM Ca level resulted in the heaviest shoots (Table 6).

Table 4. Effect of different levels of Ca in nutrient solution on tipburn and curd breakdown in the greenhouse, 1985.

Ca concn (mM)	Tipburn[z]	Curd Breakdown[z]
0.5	3.2	3.8
2.0	2.8	1.2
8.0	2.8	1.2
F-test	NS	***
LSD 0.001		0.6
CV (%)	35	26

[z]Rated 1 to 5: 1 = none, 5 = much.

NS,***Non significant and significant at the 0.1% level, respectively.

Table 5. Effect of different levels of Ca in nutrient solution on the concentration of Ca in cauliflower leaves in the greenhouse, 1985.

Ca concn (mM)	Ca 27 Aug. (% dry wt)	Ca 30 Sept. (% dry wt)
0.5	0.8	1.2
2.0	2.0	1.5
8.0	2.3	1.3
F-test	***	NS
LSD 0.001	0.4	
CV (%)	23	35

NS,***Non significant and significant at the 0.1% level, respectively.

Table 6. Effect of different Ca levels in nutrient solution on shoot and curd weight of cauliflower at harvest on 8 October in the greenhouse, 1985.

Ca concn (mM)	Shoot fresh wt ($g \cdot plant^{-1}$)	Curd fresh wt ($g \cdot plant^{-1}$)
0.5	559	101
2.0	775	441
8.0	614	470
F-test	***	***
LSD 0.001	131	97
CV (%)	18	26

***Significant at the 0.1% level.

2. Experiment Two: Effect of Ca on Tipburn and curd quality under good environmental control (1986).
Cauliflower plants grown with a substrate Ca concentration of 2.0 mM had less tipburn and curd breakdown, and improved color, shape, and quality of cauliflower curds compared to plants grown with a substrate Ca concentration of 0.5 mM (Table 7). Only curd color improved at 8.0 mM Ca instead of 2.0 mM Ca.

The Ca concentration in leaves and curds was very responsive to the substrate Ca concentration (Table 8). The leaves and curds averaged less than 0.5 ppm Ca when the substrate Ca concentration was 0.5 mM, but 1.9 to 3.2 ppm Ca with a substrate Ca concentration of 8.0 mM Ca. Higher Ca concentrations produce higher shoot, curd, and curd leaf weights (Table 9).

Table 7. Effect of different Ca concentrations in nutrient solution on dry weight Ca levels in cauliflower leaves in the greenhouse, 1986.

Ca conc. (mM)	Leaf Tipburn[z]	Curd			
		Breakdown[z]	Color[y]	Shape[x]	Quality[w]
0.5	3.0	2.1	4.7	2.8	3.6
2.0	1.1	1.2	2.8	1.9	1.8
8.0	1.0	1.0	1.3	2.0	1.8
F-test	***	***	***	***	***
LSD 0.001	0.8	0.9	1.2	0.9	1.1
CV (%)	45	55	33	41	43

[z]Rated 1 to 5: 1 = none; 5 = much.

[y]Rated 1 to 5: 1 = white; 5 = yellow.

[x]Rated 1 to 5: 1 = smooth, round; 5 = rough, irregular.

[w]Rated 1 to 5: 1 = excellent; 5 = substantially decomposed.

***Significant at the 0.1% level.

Table 8. Effect of different Ca concentrations in nutrient solution on Ca levels in cauliflower leaves in the greenhouse, 1986.

Ca concn (mM)	Ca (% dry wt)		
	Recently expanded leaves		Curd leaves
	24 April	27 May	27 May
0.5	0.4	0.1	0.1
2.0	1.2	1.7	1.0
8.0	1.9	3.2	2.0
F-test	***	***	***
LSD 0.001	0.3	0.4	0.3
CV (%)	20	20	20

***Significant at the 0.1% level.

Table 9. Effect of different Ca concentrations in nutrient solutions on shoot, curd, and curd leaf fresh weights of mature cauliflower in the greenhouse, 1986. Plants were harvested 27 May.

Ca concn (mM)	Shoot wt ($g \cdot plant^{-1}$)	Curd wt ($g \cdot plant^{-1}$)	Curd leaves ($g \cdot plant^{-1}$)
0.5	580	479	48
2.0	690	757	54
8.0	704	781	58
F-test	***	***	S
LSD 0.001, 0.001, 0.10	97	146	7
CV (%)	13	20	25

S,***Significant at the 10% and 0.1% level, respectively.

B. Field Experiments

1. Experiment one: Irrigation with Mo and Ca applications (1985). Irrigation and molybdenum treatments did not have a significant effect on the incidence of tipburn, but tipburn was less severe in plots receiving foliar Ca (Table 10). The Ca concentration in leaves harvested 30 days after transplanting was significantly higher in plots that received 5 foliar applications of 3.4 $kg \cdot ha^{-1}$ Ca, but not in leaves harvested 60 days after transplanting. The higher Ca concentrations in leaves harvested at 30 days could not be due to foliar Ca applications, because the foliar treatments were applied after this date. Calcium applications did not have a significant effect on yield.

Molybdenum application did not affect yield or the incidence of tipburn. The 5 $kg \cdot ha^{-1}$ Mo pretransplant drench increased the concentration of Mo in recently expanded leaves (Table 11).

Irrigation did not reduce tipburn, but did increase yield slightly (Table 12).

Table 10. Effect of foliar Ca applications on tipburn and Ca concentration of recently expanded leaves harvested 30 (8 Aug.) and 60 (9 Sept.) days after transplanting in the field, 1985.

Foliar Ca ($kg \cdot ha^{-1}$)	Tipburn rating[z] 18 September	Ca (% dry wt)	
		8 August	9 September
None	2.6	1.2	1.2
1.7 (5[y])	2.5	1.2	1.4
3.4 (5[y])	1.8	1.5	1.3
F-test	***	**	NS
LSD 0.001, 0.01	0.7	0.3	
CV (%)	31	20	35

[z]Rated 1 to 5: 1 = least, 5 = most.

[y]Number of applications.

,*Significant at the 1% and 0.1% level, respectively.

Table 11. Effect of soil, foliar, and seed Mo applications on Mo concentration of recently expanded leaves harvested 30 days (8 Aug.) and 60 days (9 Sept.) after transplanting in the field, 1985.

Molybdenum application amount and method	Mo (ppm, dry wt basis)	
	8 August	9 September
None	2.8	4.5
5 kg·ha^{-1} pretransplant soil drench	163	177
210 g·ha^{-1} foliar sprays (5[z])	3.7	10
2 M seed dip	3.3	4.5
F-test	***	***
LSD 0.001	25.9	30.8
CV (%)	51	53

[z]Number of applications.

***Significant at the 0.1% level.

Table 12. Effect of irrigation on cauliflower tipburn and yield in the field, 1985.

Irrigation	Tipburn rating 18 September	Yield ($kg \cdot curd^{-1}$)
None	2.2	1.6
25 $mm \cdot week^{-1}$	2.4	1.7
F-test	NS	S
LSD 0.10		0.1
CV (%)	31	19

[S]Significant at the 10% level.

2. Experiment two: Irrigation with Mo and Ca applications (1986). Recently expanded leaves harvested approximately 60 days after transplanting had slightly lower Ca concentrations when harvested from irrigated vs. unirrigated plots (Table 13).

The treatments had no effect on yield.

Table 13. Effect of irrigation applied to supply 25 $mm \cdot week^{-1}$ moisture on the Ca concentration of recently expanded leaves harvested 60 days after transplanting (8 Sept.) in the field, 1986.

Irrigation	Ca (% dry wt)
None	1.2
As needed	0.9
F-test	S
LSD 0.10	0.2
CV (%)	19

[S]Significant at the 10% level.

3. Experiment three: Soil and foliar Ca applications to control cauliflower tipburn (Spring 1987). Plot receiving 1000 $kg \cdot ha^{-1}$ Ca ppi as $CaCl_2$ or 5 weekly 3.6 $kg \cdot ha^{-1}$ Ca foliar sprays beginning 45 days after transplanting as $CaCl_2$ had a significantly lower incidence of tipburn than the controls (Table 14).

Compared to the controls, preplant incorporating $CaCl_2$ produced significantly higher Ca concentrations in recently expanded leaves harvested 30 days after transplanting (Table 15). Preplant incorporating 1000 $kg \cdot ha^{-1}$ Ca as $CaCl_2$ or $CaSO_4$ gave a significant increase in curd Ca concentration (Table 16). At 1.6 to 2.2% Ca, the Ca concentration of recently expanded leaves was over thrice the concentration of curd leaves, and the Ca concentration of curd leaves was twice the Ca concentration in curds (Tables 15 and 16)

Calcium applications did not have a significant effect on shoot or curd weight (Table 17).

Plots that received Ca treatments had an average Ca concentration ranging from 570 to 740 $mg \cdot kg^{-1}$ of soil, depending on the amount of Ca applied, while the control had 530 mg^{-1} soil (Table 18). All plots had a soil pH close to 5.0 (Table 18).

Table 14. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the incidence of tipburn in the field, Spring 1987.

Calcium amount, method of application, and source.	Number of tipburned leaves·plant^{-1} 30 July[z]
Control	7.8
340 kg·ha^{-1} ppi ($CaCl_2$)	8.7
340 kg·ha^{-1} ppi ($CaSO_4$)	6.7
1000 kg·ha^{-1} ppi ($CaCl_2$)	3.7
1000 kg·ha^{-1} ppi ($CaSO_4$)	7.8
170 kg·ha^{-1} sidedressings (2^y) ($CaCl_2$)	7.6
170 kg·ha^{-1} sidedressings (2^y) ($CaSO_4$)	7.5
3.6 kg·ha^{-1} foliar sprays (5^y) ($CaCl_2$)	2.8
F-test	**
LSD 0.01	2.7
CV (%)	25

[z]Figures are means for 15 plants per plot.

[y]Number of applications.

**Significant at the 1% level.

Table 15. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of recently expanded leaves harvested 30 (19 June) and 60 days (19 July) after transplanting in the field, Spring 1987.

Calcium amount, method of application, and source.	Ca (% dry wt) Recently expanded leaves	
	19 June	19 July
Control[z]	1.6	1.3
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	1.9	1.6
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	1.7	1.4
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.2	1.5
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	1.6	1.5
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaCl_2$)[z]	1.5	1.4
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaSO_4$)[z]	1.6	1.2
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^y) ($CaCl_2$)[z]	1.6	1.3
applying Ca vs. not applying Ca	*	
applying $CaCl_2$ vs. $CaSO_4$	**	
F-test	S	NS
LSD 0.10	0.3	
CV (%)	14	12

[z]Untreated at 30 days.

[y]Number of applications.

[NS,S]Non significant and significant at the 10% level, respectively.

Table 16. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of curd leaves and curds harvested 4 August from the field, Spring 1987.

Calcium amount, method of application, and source.	4 August Ca (% dry wt)	
	Curd leaves	Curd
Control	0.41	0.26
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.48	0.26
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.51	0.25
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.58	0.30
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.52	0.30
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	0.46	0.27
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	0.43	0.26
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^z) ($CaCl_2$)	0.44	0.24
F-test	NS	*
LSD 0.05		0.03
CV (%)	16	7

[z]Number of applications.

[NS,*]Non significant and significant at the 5% level, respectively.

Table 17. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on yield in the field, Spring 1987.

Calcium amount, method of application, and source.	Yield ($kg \cdot shoot^{-1}$)	Yield ($kg \cdot curd^{-1}$)
Control	2.5	0.7
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.2	0.7
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	2.2	0.6
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.2	0.7
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	2.5	0.6
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	2.2	0.6
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	2.3	0.7
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^z) ($CaCl_2$)	2.4	0.8
F-test	NS	NS
CV (%)	12	14

[y]Number of applications.

[NS]Non significant.

Table 18. Ammonium acetate extractable soil Ca levels and soil pH after harvest in the field, Spring 1987.

Calcium amount, method of application, and source.	Soil Ca (mg Ca·kg soil^{-1})	Soil pH
Control	530	5.1
340 kg·ha^{-1} ppi ($CaCl_2$)	660	5.0
340 kg·ha^{-1} ppi ($CaSO_4$)	600	5.1
1000 kg·ha^{-1} ppi ($CaCl_2$)	740	5.0
1000 kg·ha^{-1} ppi ($CaSO_4$)	740	5.0
170 kg·ha^{-1} sidedressings (2^z) ($CaCl_2$)	640	4.9
170 kg·ha^{-1} sidedressings (2^z) ($CaSO_4$)	570	5.0
3.6 kg·ha^{-1} foliar sprays (5^z) ($CaCl_2$)	600	5.0
F-test	***	NS
LSD 0.001	160	
CV (%)	7	4

^{z}Number of applications.

NS,***Non significant and significant at the 0.1% level, respectively.

4. Experiment four: Soil and foliar Ca applications to control tipburn of cauliflower (Fall 1987). Although the F-test was significant, the incidence of tipburn in plots receiving Ca treatments was not significantly different from the control (Table 19).

The average Ca concentration in recently expanded leaves harvested from the control 30 days after transplanting was 1.7% Ca on a dry weight basis. When $CaCl_2$ was preplant incorporated at a rate of 340 and 1000 $kg \cdot ha^{-1}$ actual Ca, Ca concentrations were significantly higher at 1.9 and 2.1% Ca, respectively (Table 20).

Calcium applications did not have a significant effect on curd leaf and curd Ca concentration (Table 21) and shoot and curd weight (Table 22).

In general, Ca applications resulted in higher soil Ca levels. Although there was a statistically significant difference in pH, the actual difference was small and does not require further consideration (Table 23).

Table 19. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the incidence of tipburn in field, Fall 1987.

Calcium amount, method of application, and source.	Number of tipburned leaves·plant^{-1} 21 September[z]
Control	3.6
340 kg·ha^{-1} ppi ($CaCl_2$)	3.6
340 kg·ha^{-1} ppi ($CaSO_4$)	4.4
1000 kg·ha^{-1} ppi ($CaCl_2$)	5.5
1000 kg·ha^{-1} ppi ($CaSO_4$)	1.3
170 kg·ha^{-1} sidedressings (2^y) ($CaCl_2$)	5.6
170 kg·ha^{-1} sidedressings (2^y) ($CaSO_4$)	5.5
3.6 kg·ha^{-1} foliar sprays (6^y) ($CaCl_2$)	1.8
F-test	S
LSD 0.10	2.7
CV (%)	47

[z]Figures are means for -- plants per plot.

[y]Number of applications.

[S]Significant at the 10% level.

Table 20. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of recently expanded leaves harvested 30 (30 July) and 60 days (28 Aug.) after transplanting in the field, Fall 1987.

Calcium amount, method of application, and source.	Ca (% dry wt) Recently expanded leaves	
	30 July	28 August
Control[z]	1.7	1.5
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	1.9	1.8
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	1.8	1.6
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.1	1.4
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	1.8	1.4
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaCl_2$)[z]	1.7	1.5
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaSO_4$)[z]	1.7	1.5
3.6 $kg \cdot ha^{-1}$ foliar sprays (6^y) ($CaCl_2$)[z]	1.6	1.4
applying Ca vs. not applying Ca	**	
applying $CaCl_2$ vs. $CaSO_4$	*	
F-test	S	NS
LSD 0.10	0.2	
CV (%)	9	16

[z]Untreated at 30 days.

[y]Number of applications.

[NS,S]Non significant and significant at the 10% level, respectively.

Table 21. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of curd leaves and curds harvested 4 August from the field, Fall 1987.

Calcium amount, method of application, and source.	21 September Ca (% dry wt)	
	Curd leaves	Curd
Control	0.63	0.20
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.70	0.21
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.88	0.20
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.64	0.21
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.64	0.16
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	0.73	0.20
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	0.74	0.21
3.6 $kg \cdot ha^{-1}$ foliar sprays (6^z) ($CaCl_2$)	0.64	0.17
F-test	NS	NS
CV (%)	21	15

^{z}Number of applications.

^{NS}Non significant.

Table 22. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on yield in the field, Fall 1987.

Calcium amount, method of application, and source.	Yield ($kg \cdot shoot^{-1}$)	Yield ($kg \cdot curd^{-1}$)
Control	3.9	1.7
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	4.1	1.7
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	4.1	1.8
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	3.6	1.7
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	3.9	1.4
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	3.8	1.9
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	3.5	1.7
3.6 $kg \cdot ha^{-1}$ foliar sprays (6^z) ($CaCl_2$)	3.3	1.5
F-test	NS	NS
CV (%)	9	14

[z]Number of applications.

[NS]Non significant.

Table 23. Ammonium acetate extractable soil Ca levels and soil pH after harvest in the field, Fall 1987.

Calcium amount, method of application, and source.	Soil Ca (mg Ca·kg soil^{-1})	Soil pH
Control	730	5.0
340 kg·ha^{-1} ppi ($CaCl_2$)	970	5.1
340 kg·ha^{-1} ppi ($CaSO_4$)	820	5.3
1000 kg·ha^{-1} ppi ($CaCl_2$)	970	5.2
1000 kg·ha^{-1} ppi ($CaSO_4$)	930	5.3
170 kg·ha^{-1} sidedressings (2^z) ($CaCl_2$)	860	5.0
170 kg·ha^{-1} sidedressings (2^z) ($CaSO_4$)	770	5.1
3.6 kg·ha^{-1} foliar sprays (6^z) ($CaCl_2$)	730	5.2
F-test	*	*
LSD 0.001	170	0.2
CV (%)	11	2

[z]Number of applications.

*Significant at the 5% level.

5. Experiment five: Soil and foliar Ca applications to control cauliflower tipburn (1988). Calcium applications did not affect the incidence of tipburn (Table 24).

Recently expanded leaves harvested 60 days after transplanting from plots with preplant incorporated $CaCl_2$ suppling 1000 $kg \cdot ha^{-1}$ Ca and foliar applications of $CaCl_2$ had significantly higher concentrations of Ca than the controls (Table 25). Preplant incorporated $CaCl_2$ and $CaSO_4$ supplying 1000 $kg \cdot ha^{-1}$ resulted curd Ca concentrations that were significantly higher than the controls (Table 26).

Curd weight was significantly higher with 2 $CaCl_2$ sidedressings (Table 27).

There was no significant difference in soil Ca levels. However, the plots receiving foliar Ca the highes soil Ca levels. Although differences in soil pH were not statistically significant, the actual difference between the pH of the plots receiving foliar Ca and the other plots is considerable (Table 28). This appears due to the placement of all of the foliarly treated plots in an area of the field with high pH and soil Ca levels.

Table 24. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the incidence of tipburn in the field, 1988.

Calcium amount, method of application, and source.	Number of tipburned leaves·plant^{-1} at curd harvest[z]
Control	2.1
340 kg·ha^{-1} ppi ($CaCl_2$)	3.3
340 kg·ha^{-1} ppi ($CaSO_4$)	1.4
1000 kg·ha^{-1} ppi ($CaCl_2$)	6.6
1000 kg·ha^{-1} ppi ($CaSO_4$)	2.6
170 kg·ha^{-1} sidedressings (2^y) ($CaCl_2$)	3.0
170 kg·ha^{-1} sidedressings (2^y) ($CaSO_4$)	2.7
3.6 kg·ha^{-1} foliar sprays (5^y) ($CaCl_2$)	2.2
F-test	NS
CV (%)	67

[z]Figures are means for -- plants per plot.

[y]Number of applications.

[NS]Non significant.

Table 25. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of recently expanded leaves harvested 30 (22 June) and 60 days (22 July) after transplanting in the field, 1988.

Calcium amount, method of application, and source.	Ca (% dry wt) Recently expanded leaves	
	30 June	28 July
Control[z]	2.3	1.2
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.6	1.5
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	2.5	1.6
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	2.7	1.8
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	2.4	1.3
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaCl_2$)[z]	2.1	1.6
170 $kg \cdot ha^{-1}$ sidedressings (2^y) ($CaSO_4$)[z]	2.4	1.4
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^y) ($CaCl_2$)[z]	2.5	1.9
applying Ca vs. not applying Ca	S	
applying $CaCl_2$ vs. $CaSO_4$	NS	
F-test	NS	S
LSD 0.10		0.4
CV (%)	10	16

[z]Untreated at 30 days.

[y]Number of applications.

[NS,S]Non significant and significant at the 10% level, respectively.

Table 26. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on the dry weight Ca concentration of curd leaves and curds combined from several harvests from the field, 1988.

Calcium amount, method of application, and source.	Ca (% dry wt)	
	Curd leaves	Curd
Control	0.44	0.18
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.41	0.18
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.51	0.23
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.44	0.26
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.48	0.25
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	0.52	0.23
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	0.45	0.22
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^z) ($CaCl_2$)	0.42	0.22
F-test	NS	**
LSD 0.01		0.05
CV (%)	13	10

[z]Number of applications.

NS,**Non significant and significant at the 1% level, respectively.

Table 27. The effect of soil and foliar applications of $CaCl_2$ and soil applications of $CaSO_4$ on yield in the field, 1988.

Calcium amount, method of application, and source.	Yield ($kg \cdot curd^{-1}$)[z]
Control	0.62
340 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.61
340 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.77
1000 $kg \cdot ha^{-1}$ ppi ($CaCl_2$)	0.59
1000 $kg \cdot ha^{-1}$ ppi ($CaSO_4$)	0.70
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaCl_2$)	0.82
170 $kg \cdot ha^{-1}$ sidedressings (2^z) ($CaSO_4$)	0.67
3.6 $kg \cdot ha^{-1}$ foliar sprays (5^z) ($CaCl_2$)	0.53
F-test	*
LSD	0.17
CV (%)	15

[z]Number of applications.

*Significant at the 5% level.

Table 28. Ammonium acetate extractable soil Ca levels and soil pH after harvest in the field, 1988.

Calcium amount, method of application, and source.	Soil Ca (mg Ca·kg soil^{-1})	Soil pH
Control	1440	6.3
340 kg·ha^{-1} ppi ($CaCl_2$)	1470	6.1
340 kg·ha^{-1} ppi ($CaSO_4$)	1320	6.1
1000 kg·ha^{-1} ppi ($CaCl_2$)	1510	6.0
1000 kg·ha^{-1} ppi ($CaSO_4$)	1400	6.2
170 kg·ha^{-1} sidedressings (2^z) ($CaCl_2$)	1470	6.2
170 kg·ha^{-1} sidedressings (2^z) ($CaSO_4$)	1400	6.3
3.6 kg·ha^{-1} foliar sprays (5^z) ($CaCl_2$)	2110	6.9
F-test	NS	NS
CV (%)	19	6

^{z}Number of applications.

^{NS}Non significant.

6. Experiments three, four, and five: Combined data excluding foliar treatments (1987-1988). The number of tipburned leaves·plant^{-1} was negatively correlated with soil Ca levels. As the value for soil Ca concentration increases from 360 to 1800 mg Ca·kg soil^{-1} the predicted number of tipburned leaves·plant^{-1} decreases from 7 to 2 (Figure 1).

The concentration of Ca in recently expanded leaves at 30 days was positively correlated with soil Ca (Figure 2). There was not a significant correlation between recently expanded leaves harvested at 60 days and soil Ca.

Tipburn was positively correlated with Curd Ca concentration. With a Ca concentration of 0.11% in the curds the predicted number of tipburned leaves·plant^{-1} is 1, and with a Ca concentration of 0.32% in the curds the predicted number of tipburned leaves·plant^{-1} is 8 (Figure 3). Although there was a significant negative correlation between curd and curd leaf Ca concentration, the relationship was not highly significant like the two previous correlations (Figure 4). There was no significant correlation between the concentration of Ca in the leaves and tipburn.

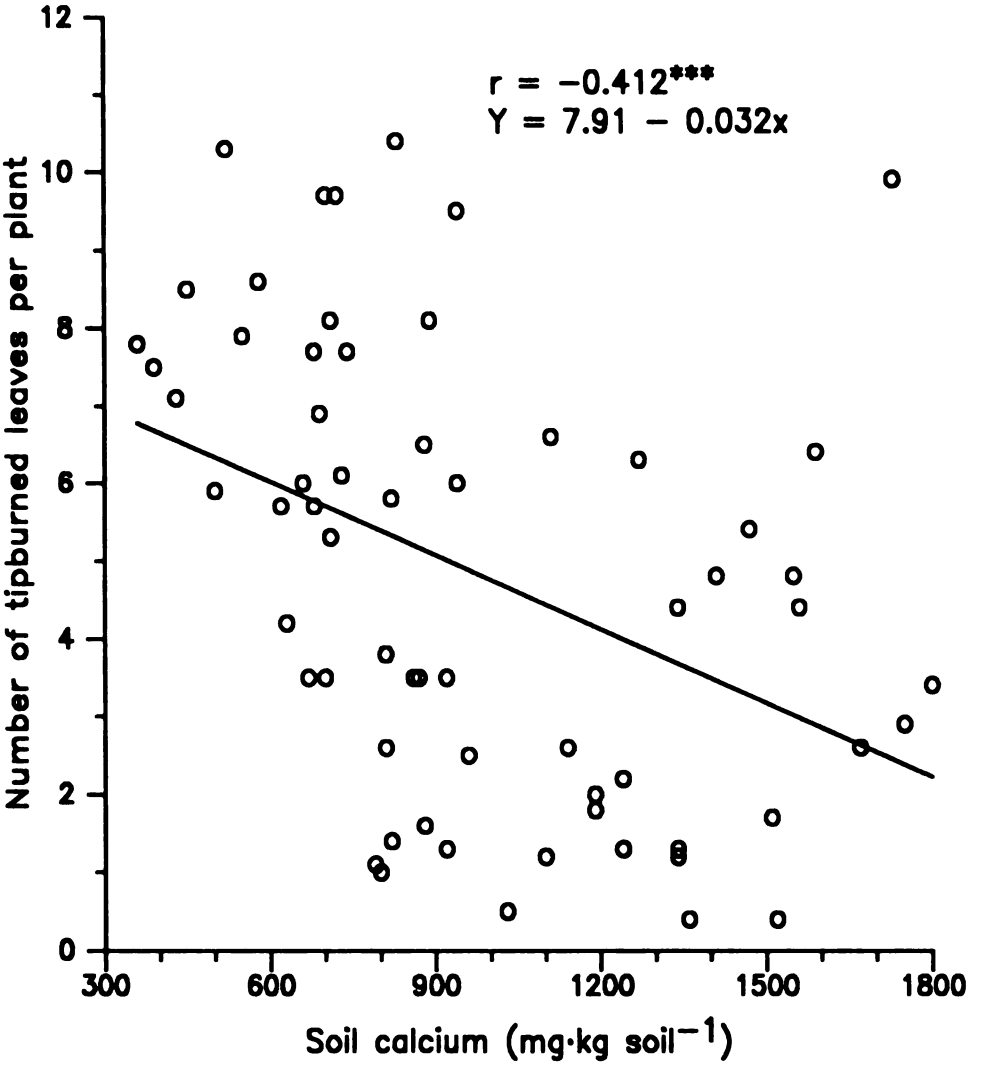

Figure 1. The relationship of the incidence of cauliflower tipburn to soil Ca. Based on combined data, excluding foliar treatments, from 1987 and 1988 experiments.

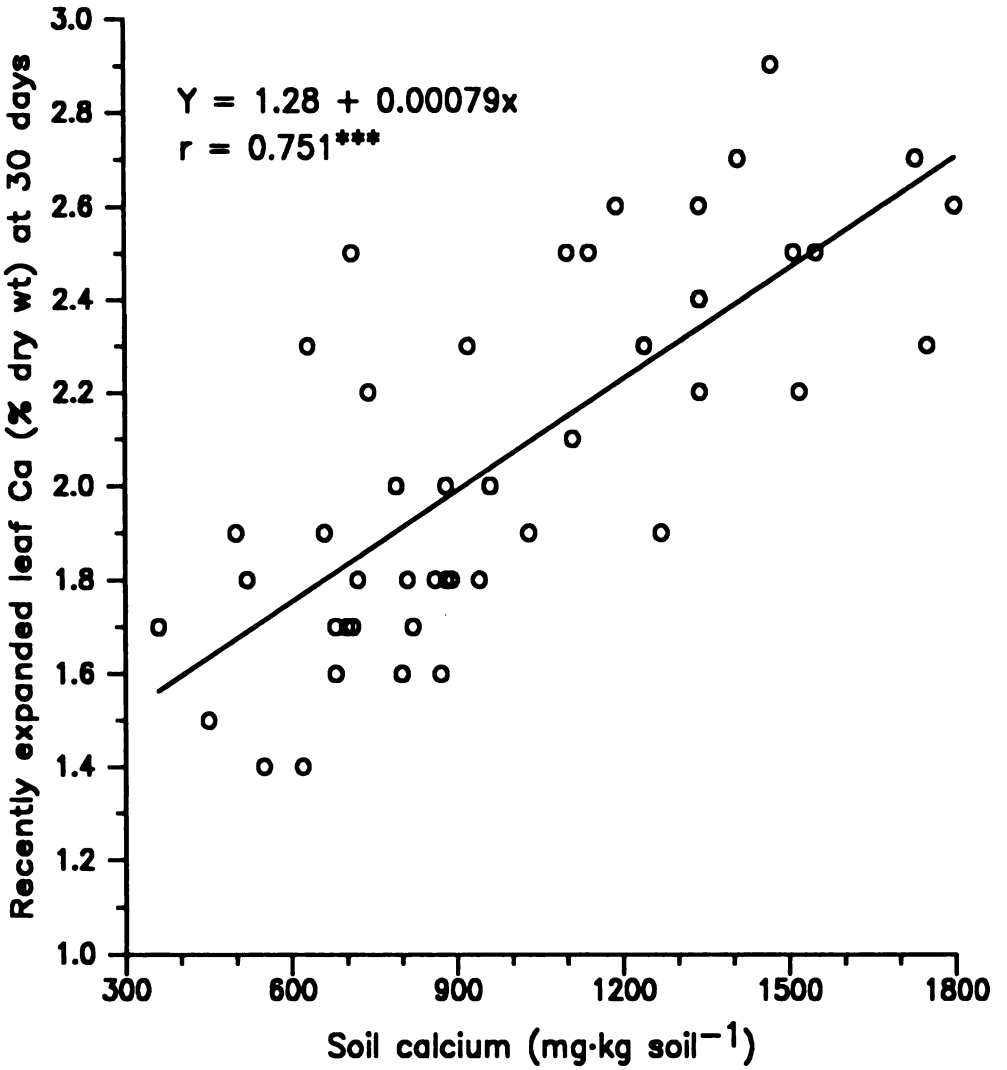

Figure 2. The relationship of the concentration of Ca in recently expanded leaves harvested 30 days after transplanting to soil Ca. Based on combined data, excluding foliar and sidedressed treatments, from 1987 and 1988 experiments.

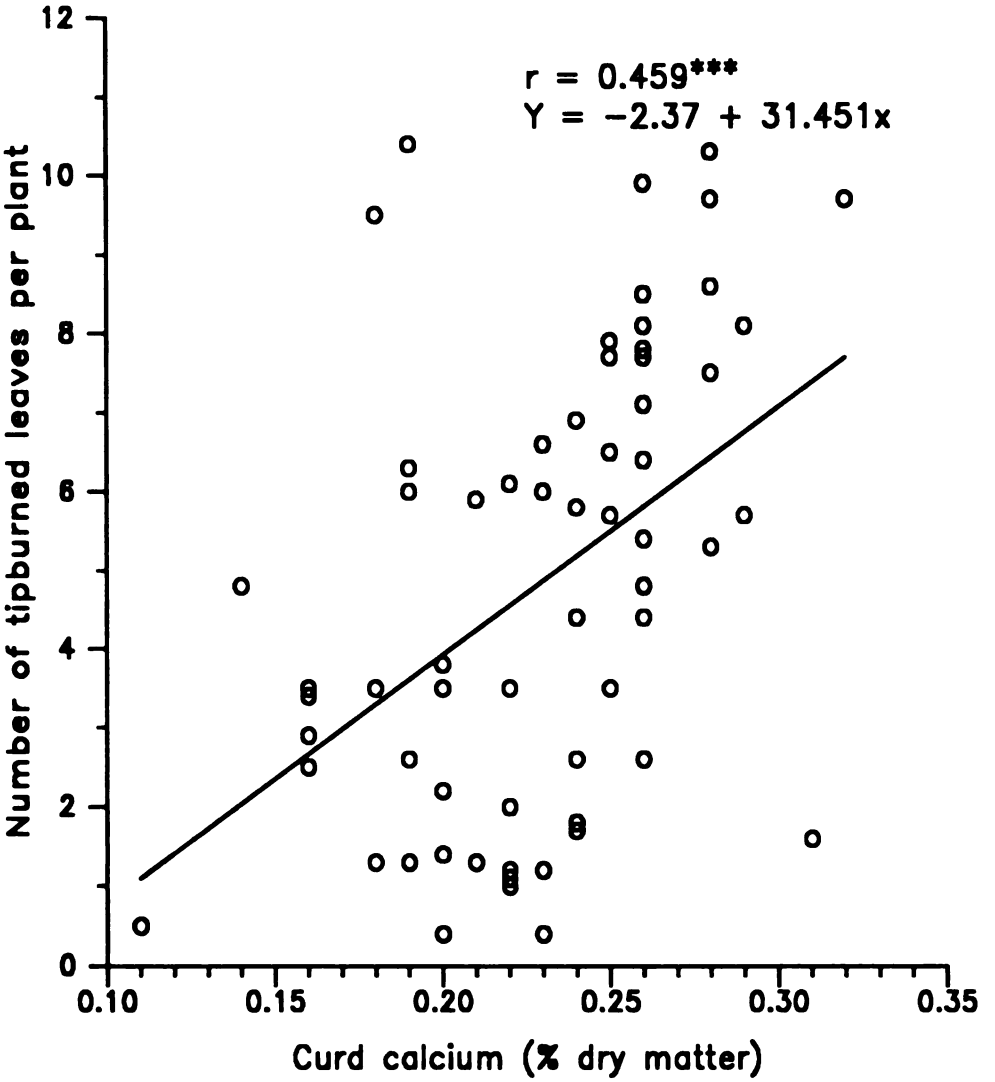

Figure 3. The relationship of the incidence of cauliflower tipburn to curd Ca based on combined data, excluding foliar treatments, from 1987 and 1988 experiments.

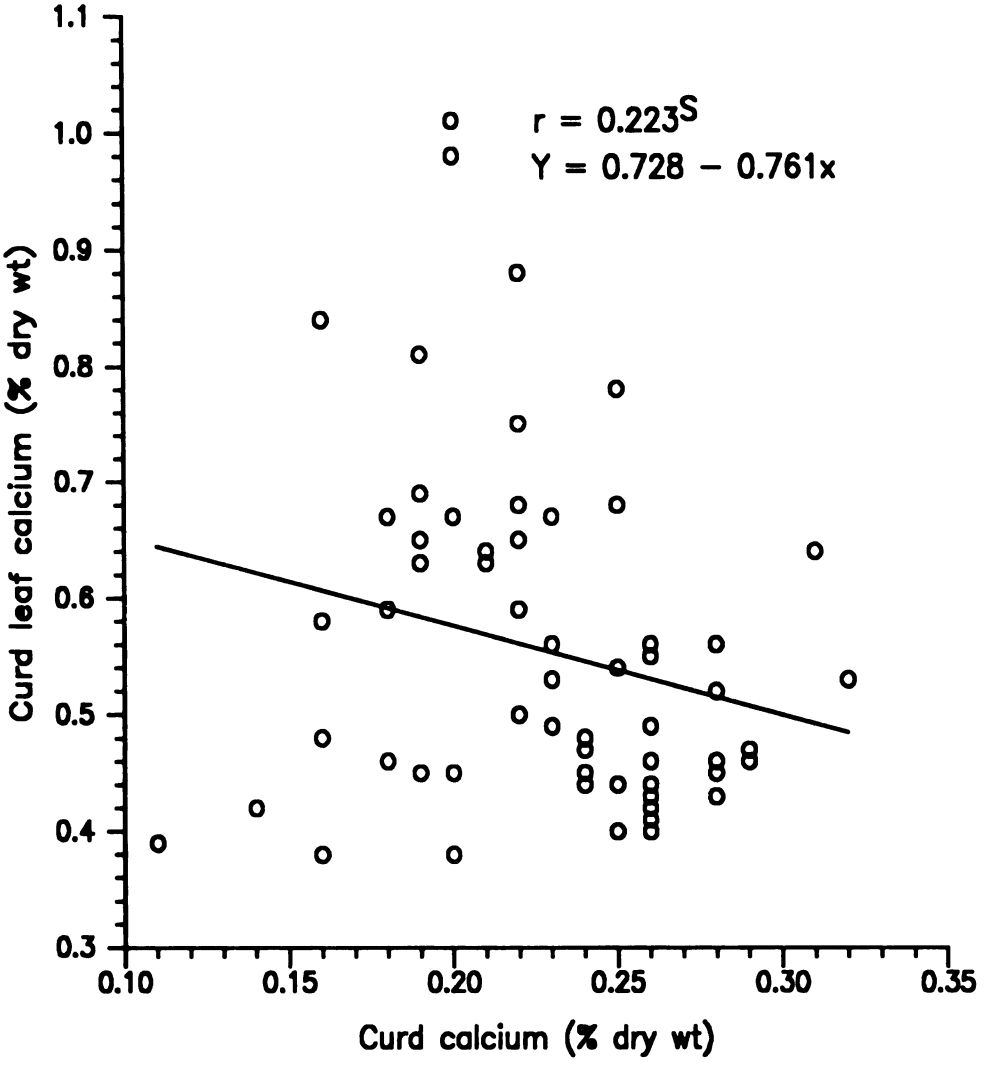

Figure 4. The relationship of curd leaf Ca to curd Ca. Based on combined data, excluding foliar treatments, from 1987 and 1988 experiments.

V. DISCUSSION

The results of greenhouse and field experiments suggest a link between Ca nutrition of cauliflower and the development of tipburn. With good environmental control and a substrate Ca concentration of 0.5 mM, greenhouse-grown cauliflower plants exhibited tipburn and curd breakdown, while with 2.0 and 8.0 mM Ca, there was less tipburn and curd breakdown (Table 7). When the Ca concentration in the substrate was relatively low, the Ca concentration in the leaf tissue was relatively low, and when Ca was high in the substrate Ca was higher in the leaves (Table 8).

With poor environmental control - i.e. moving stress and poor temperature control - and the same concentrations of Ca in the substrate (0.5, 2.0 and 8.0 mM), the severity of tipburn was not significantly different among the treatments (Table 4). Even though substrate Ca was 16 times more concentrated at 8.0 mM than at 0.5 mM, there was no significant difference in the Ca concentration of leaves harvested after one month of poor temperature control (Table 5). These data suggest that poor environmental conditions promote tipburn by limiting Ca translocation to the leaves. However, it is difficult to explain why, with 0.5 mM Ca in the substrate, leaf Ca concentration was so much higher

under poor environmental control (1.2%, Table 5) than under good environmental control (0.1%, Table 8). Perhaps under poor environmental control, Ca that was taken up was readily translocated to the curd after uptake, but the total amount of Ca available was limited with 0.5 mM Ca. Curd breakdown was significantly lower with a substrate Ca concentration of 2.0 and 8.0 mM Ca compared to 0.5 mM Ca (Table 4). Unfortunately, curd Ca concentration was not evaluated.

In the field, more soil Ca correlated with less tipburn (Figure 1) and greater concentrations of Ca in leaves harvested 30 days after transplanting (Figure 2). These correlations are supported by the greenhouse results mentioned above and by similar results reported by Maynard et al. (1981). Higher soil Ca levels did not correlate with higher levels of Ca in curd leaves, even though there were fewer tipburned leaves when soil Ca was relatively high. It may be that it is difficult to obtain uniform tissue samples of curd leaves, and that Ca differences are small between sufficient and deficient levels. In addition, there was no significant correlation between 60 day leaf Ca concentrations and soil Ca. Perhaps as the plants mature, environmental factors become more important than soil Ca levels in determining the amount of Ca taken up and translocated to the leaves.

The primary factors controlling the concentration of Ca in recently expanded leaf tissue and the concentration of Ca in curd tissue appear to be different. Although ppi $CaCl_2$

and $CaSO_4$ resulted in higher soil (Tables 18 and 24) and curd (Tables 16 and 26) Ca, leaves responded to $CaCl_2$, but not $CaSO_4$ (Tables 15 and 20). The Ca concentration in leaves harvested at 30 days was higher when $CaCl_2$ was applied (Tables 15 and 20) and soil Ca was significantly higher than the controls (Tables 18 and 23), but when extractable soil Ca did not increase with $CaCl_2$ application, neither did leaf Ca (Tables 25 and 28). Only $CaCl_2$ significantly reduced tipburn (Table 14).

The Ca concentration in the curds seems to respond to Ca applications to the soil, while not responding to soil Ca as measured by the ammonium acetate extraction method. In experiment 3, curd Ca concentrations and soil Ca were higher in plots receiving ppi $CaCl_2$ and $CaSO_4$ treatments (Tables 16 and 18). In experiment 4, soil Ca was higher in the ppi $CaCl_2$ and $CaSO_4$ treated plots, but curd Ca was not higher (Tables 21 and 23). Then, in experiment 5, curd Ca was higher in the ppi $CaCl_2$ and $CaSO_4$ treated plots, but soil Ca was not higher (Tables 26 and 28). An alternative explanation is that the curds responded to ppi Ca under poor growing conditions. Yield and weather data show that the growing conditions were better during the fourth experiment than during the third and fifth experiments (Tables 17, 22, and 27; Appendix).

Competition for Ca between expanding leaves and the curd may promote tipburn. In the field, when the Ca concentration in the curd was comparatively high, there was

more tipburn (Figure 3). If this was a result of competition for Ca, it would follow that there would be less Ca in the leaves as Ca in the curds increased and vice versa. Although there was a negative correlation between curd and curd leaf Ca concentration, the relationship was not highly significant (Figure 4). If the curds and the expanding leaves are competitive sinks for Ca, their relative competitiveness may be weather related. Von Krug et al. (1972) found low relative humidity (RH) prevented Ca deficiency in young cauliflower leaves while fluctuating RH prevented Ca deficiency in curds.

When the cauliflower plants were under stress, chloride (Cl^-) may have had a detrimental effect on the cauliflower plants. Islam et al. (1987) found that maximum growth of a variety of plant species occurred at a higher Ca concentration when $CaSO_4 \cdot 2H_2O$ instead of $CaCl_2$ was used for the source of Ca. They concluded that the plants were injured by Cl^- when the Ca concentration was optimal. In the greenhouse experiment with poor environmental control, vegetative shoot weight was the highest with a Ca concentration of 2.0 mM. Vegetative shoot weight was lower with either 0.5 or 8.0 mM Ca in the substrate. A high Cl^- level in the 8.0 mM Ca solution may have limited vegetative shoot growth. However, there was not a similar effect on curd weight (Table 6). In field experiment 5 (1988), which was grown under the harshest weather conditions, Cl^- may have also had a detrimental effect. During 1988 the

temperature often exceeded 30°C with the temperature reaching 38°C on several days. There was little rainfall and even though the field was irrigated, the plants suffered some heat and drought stress (Appendix). There was no significant difference in tipburn, but the highest number of tipburned leaves per plant were in plots receiving 1000 $kg \cdot ha^{-1}$ Ca.

Foliar-applied Ca appears to be a very promising treatment to avoid tipburn in cauliflower. While foliar-applied Ca did not completely prevent tipburn, plots receiving foliar-applied Ca had significantly less tipburn in two experiments (Tables 10 and 14). In the last three field experiments the leaves exhibiting tipburn were counted. In the experiment with the most tipburn, plots receiving foliar-applied Ca had only 2.8 tipburned leaves per plant, compared to 7.8 tipburned leaves per plant on the controls (Table 14). The average number of leaves with tipburn never exceeded 2.8 per plant in plots receiving foliar Ca (Tables 14, 19, 24). Generally, this should be an acceptable level of tipburn.

Furthermore, in experiment 5, tipburn tended to develop about a week after the last application. Therefore, the effectiveness of foliar-applied Ca would probably increase if Ca was applied based on plant growth, perhaps using degree days, instead of on a weekly schedule.

Soil-applied Ca shows some promise for lowering the incidence of tipburn in the field, but the effect soil-

applied Ca has on tipburn may depend on the weather conditions. Plots which had $CaCl_2$ applied at the 1000 $kg \cdot ha^{-1}$ Ca rate had significantly less tipburn in experiment 3 (Table 14), but the most tipburn in experiment 5 (Table 24). Rainfall was quite low and the temperatures were too high for optimal growth during both of these experiments (Appendix; Tables 17 and 27). Perhaps under the very stressful conditions that prevailed during experiment 5, excess chloride resulted in an increased level of tipburn. In the fourth experiment the number of tipburned leaves per plant was low when 1000 $kg \cdot ha^{-1}$ Ca was applied as $CaSO_4$. During experiment 4, the rainfall was high (Appendix) and growth was good (Table 22). The high rainfall may have leached some of the $CaCl_2$ out of the root zone and promoted the dissolution and distribution of $CaSO_4$, thus causing it to be more effective in reducing tipburn. Gupta and Singh (1988) found that in an alkali soil $CaCl_2$ provided a quick burst of Ca that quickly leached from the soil, while $CaSO_4$ provided a more sustained level of Ca that did not peak as high.

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Chapter 3

MOLYBDENUM APPLICATIONS IMPROVE BROCCOLI YIELD

I. ABSTRACT

In a greenhouse experiment, broccoli (*Brassica oleracea* var. *italica*) was grown in sand and watered with a nutrient solutions containing 0, 0.1, 1.0, 10, 100, or 1000 μM Molybdenum (Mo). The plants grew well with 0 to 100 μM Mo and there was no significant difference in head yield.

In field experiments, broccoli was exposed to several treatments.The treatments included: 2.2 or 4.1 $kg \cdot ha^{-1}$ Mo as sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$) preplant incorporated (ppi); and 0.15, 0.30, or 0.40 $kg \cdot ha^{-1}$ Mo as $Na_2MoO_4 \cdot 2H_2O$ in 5 or 6 weekly foliar sprays from transplanting to harvest. Foliar treatments of 0.3 and 0.4 $kg \cdot ha^{-1}$ Mo had highest levels of molybdenum in leaves at harvest. Only ppi treatments resulted in significantly higher yields.

II. INTRODUCTION

Severe Mo deficiency causes whiptail of cauliflower (*Brassica oleracea* var. *botrytis*) and broccoli (*Brassica oleracea* var. *italica*) (Hewitt and Jones, 1947; Plant, 1951). Whiptail occurs when the leaf midrib extends normally, but the leaf lamina does not expand. The optimum concentration of Mo in broccoli leaf tissue for maximum yield has not been reported. In the field, broccoli plants sometimes show symptoms resembling nitrogen deficiency when there is an adequate nitrogen supply. Intervainal chlorosis has been observed to be a pre-whiptail symptom of broccoli (Waring, 1950). Mild molybdenum deficiency resembles nitrogen deficiency because molybdenum is required for (NO_3^--N) assimilation (Hewitt, 1975). Therefore molybdenum deficiency could, in a sense, cause nitrogen deficiency. Field experiments were performed to determine if the yield of field-grown broccoli could be increased by molybdenum application. A greenhouse experiment was performed to determine what leaf tissue concentrations of molybdenum correspond to maximum yield.

III. MATERIALS AND METHODS

A. Introduction

Experiments were conducted in the Plant Science Greenhouse and in the field at the Horticultural Research Center, Michigan State University, East Lansing, Michigan to determine whether Mo applications could increase broccoli yield. 'Packman' broccoli was used in all experiments. Tissue analysis was the same for all experiments.

B. General Field Practices

Fields planted to broccoli were broadcast with 45 $kg \cdot ha^{-1}$ nitrogen (N), 40 $kg \cdot ha^{-1}$ phosphorus (P), and 75 $kg \cdot ha^{-1}$ potassium (K) and then plowed. Before transplanting 700 $g \cdot ha^{-1}$ trifluralin, 56 $kg \cdot ha^{-1}$ N, and 4.6 $kg \cdot ha^{-1}$ boron (B) were disked in. At transplanting, 240 ml of a starter solution containing 0.95 $ml \cdot liter^{-1}$ chlorpyrifos and 35 $g \cdot liter^{-1}$ 10N-23P-14K fertilizer was applied to each plant as it was set in the soil. The plants were set with a single row mechanical transplanter.

The plants were sidedressed with 56 $kg \cdot ha^{-1}$ N (165 $kg \cdot ha^{-1}$ NH_4NO_3) 3 and 7 weeks after transplanting. The broccoli plots were single rows 9.1 m long by 1.2 m wide, with 30 cm between plants. The transplants were grown in 96-cell flats at the Plant Science Greenhouse. These cells

are 4 cm high, 5.5 by 4 cm wide at the top, and hold about 30 cc of media.

All foliar treatments were applied with a hand carried, carbon dioxide (CO_2) powered sprayer at 200 kPa pressure in 370 liter·ha^{-1} water. A 9508E spray tip was used in 1986. In 1987 and 1988 a TJ60-8006E spray tip was used to provide better coverage. This tip has dual orifices, one spraying forward and the other rearward at a 60° angle. A nonionic surfactant was added to the tank mixes. The surfactants used were Triton AG-98 0.1% (v/v) in 1986, and Silwet L-77 0.075% (v/v) in 1987 and 1988. Molybdenum was applied as sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$), but amounts applied are presented in terms of elemental Mo.

C. Tissue analysis

At least 6 leaves collected from separate plants in each plot were combined to form one sample for mineral analysis. Samples were not taken from plants at the ends of the rows or from unusual plants. Leaf samples were dipped 6 to 8 times in deionized water and shaken to remove excess water, then dipped 6 to 8 times in 0.15 N hydrochloric acid (HCl) and shaken to remove excess water. Then this rinsing method was repeated two more times in separate containers of deionized water. The washing process takes about a minute. The samples were forced-air dried at 70°C and ground in a Wiley mill to pass through a 1.3 mm screen. The ground

tissue was redried at 70°C for at least 24 hours and weighed for ashing.

The plant tissue samples were dry ashed. The tissue was weighed into Coors porcelain crucibles using a Mettler PC 440 electronic balance and ashed at 550°C for 8 hours in a muffle furnace. The ashed tissue was then dissolved in 10 ml of 1.5 N HCl. The samples were rinsed out of the crucibles and brought up to volume with 1.5 N HCl. The amount of tissue and the volume of solution were varied to keep the Mo concentration within an acceptable range for analysis. Prior to analysis, the samples were filtered through Schleicer & Schuell number 588 analytical filter paper.

The samples were analyzed with an Instrumentation Laboratory Video 12 atomic absorption - atomic emission spectrophotometer. Molybdenum was analyzed by nitrous oxide-acetylene (N_2O-C_2H_2) flame, atomic absorption spectrophotometry with an Instrumentation Laboratory hollow cathode-Mo lamp at a wavelength of 313.3 nm and a bandwidth of 0.5 nm. The samples were aspirated at a 6 $ml \cdot min^{-1}$ flow rate.

D. Statistical Analysis

All data was subjected to analysis of variance and mean differences were compared by LSD. The software used was MSTAT.

E. Greenhouse Experiment

1. Experiment one: Mo nutrition in sand culture (1988). To remove impurities, coarse silica sand in pots was leached with 10% (v/v) sulfuric acid (H_2SO_4), followed by several liters of deionized water, and subsequently with several liters of nutrient solution (Table 1). The sand held a liter of solution when saturated. The pots were 22 cm tall and 26 cm in diameter at the top (8 liter pots) and held approximately 7,000 cc of sand. The nutrient solutions had a pH of 6.5 to 6.6, a conductance of 1.9 to 2.0 $mS \cdot cm^{-1}$, and were prepared using deionized water and reagent grade chemicals.

On 22 March five broccoli seeds were planted in each pot. The pots were covered with Reynolds 906 cellophane film to keep the sand moist until the seedlings were 1 cm tall. The plants were thinned to two plants per pot on 7 April and to one plant per pot on 12 April. Throughout the experiment the plants were watered by hand with nutrient solution when the top centimeter of the sand became dry.

The experiment was a randomized complete block design with six replications. Each block consisted of a row of 6 treated plants. A guard plant was placed at each end of the rows. Each greenhouse bench had two rows of 8 plants on it. The treatments were; no added Mo, 0.1, 1.0, 10, 100, and 1000 μM Mo. A separate nutrient solution was mixed for each treatment. The treatments were applied from before the seeds were planted until the plants were harvested.

Daytime temperatures ranged from 26 to 40°C. Night temperatures ranged from 20 to 26°C. The plants were grown under natural light providing about 12 $mol \cdot m^{-2} \cdot day^{-1}$ PPF.

The whole plants were harvested as they matured on 26 and 30 May and 2 and 6 June, depending on when the individual plants matured. At harvest, a recently expanded leaf was removed from each plant for mineral analysis. Fresh and dry weights of the plant roots, stems, leaves, and heads were recorded.

Table 1. Nutrient solution composition.

Nutrient Salt	Concentration
$(NH_4)_2HPO_4$	1.0 mM
NaH_2PO_4	1.0 mM
$MgSO_4 \cdot 7H_2O$	1.0 mM
$Ca(NO_3)_2 \cdot 4H_2O$	4.0 mM
KNO_3	6.0 mM
$CuSO_4 \cdot 5H_2O$	0.50 μM
$MnSO_4 \cdot H_2O$	2.0 μM
$ZnSO_4 \cdot 7H_2O$	2.0 μM
H_3BO_3	25 μM
Fe-EDTA[z]	30 μM
KCl	50 μM

[z]Fe-EDTA = Sodium ferric ethylenediamine tetraacetate

F. Field Experiments

1. Experiment one: Soil and foliar-applied Mo (Spring 1986). Broccoli was seeded in flats on 9 April. The transplants were set in the field on 8 May. The soil was a Miami loam with 2.5% organic matter and a pH of 6.0.

The treatments listed in Table 2 were arranged in a randomized complete block design with 3 replications. The strip applied Mo was put on after transplanting. The foliar treatments were applied on 11 and 17 June.

Table 2. List of treatments[z].

1. Control
2. 4.1 $kg \cdot ha^{-1}$ Mo in 1000 liters of water, applied in a strip next to the row
3. 150 $g \cdot ha^{-1}$ Mo foliar spray
4. 300 $g \cdot ha^{-1}$ Mo foliar spray

On 25 June, heads from 10 neighboring plant in each plot were harvested and weighed. Recently expanded leaves were harvested for Mo analysis on the same day.

2. Experiment two: Soil and foliar-applied Mo (Fall 1986). Broccoli was seeded in flats on 13 August and set in the field on 10 September. The treatments applied were the same as the previous experiment except that 4.1 $kg \cdot ha^{-1}$ Mo was preplant incorporated (ppi) 10 to 15 cm deep with a

rototiller instead of being applied in a strip. Foliar treatments were applied weekly for 9 weeks beginning on 12 September and ending on 6 November

On 9 Nov., heads from 10 neighboring plants in each plot were harvested and weighed, and recently expanded leaves were harvested for Mo analysis.

3. Experiment three: Soil and foliar-applied Mo (Summer 1987). Broccoli was sown in flats on 24 April. The plants were set in the field on 20 May. The soil was a Marlette fine sandy loam with 2% organic matter and a pH of 5.0.

The treatments are listed in Table 3. Foliar treatments were applied weekly for 5 weeks beginning 10 June and ending 8 July.

Table 3. List of treatments.

1. Control
2. 10 mM Mo drench applied to the plants in flats just before transplanting[z]
3. 220 $g \cdot ha^{-1}$ Mo foliar application
4. 2.2 $kg \cdot ha^{-1}$ Mo ppi 10 to 15 cm deep with a rototiller

[z]Modified in experiments 4 and 5 as described in the text.

All heads were harvested and weighed on 6 and 10 July. On 6 July, recently expanded leaves were harvested for Mo analysis.

4. Experiment four: Soil and foliar-applied Mo (Fall 1987). The preceding experiment was repeated, but the 10 mM drench was reduced to a 5 mM drench.

The broccoli was seeded 31 May 1987, and transplanted into an area adjacent to the previous experiment on 29 June. The foliar treatment was applied in six weekly sprays from 1 July to 5 August. Leaf samples were harvested on 14 August and all heads were harvested on 14, 18 and 20 August.

5. Experiment five: Soil and foliar-applied Mo (Summer 1988). The preceding experiment was repeated, but instead of a 5.0 mM Mo drench, the transplant roots were dipped into a 5.0 mM Mo solution for 10 seconds. The Mo solution did not touch the leaves.

The broccoli was seeded 13 April and transplanted into the field on 13 May. The soil was a Capac loam with a pH of 6.3. The foliar treatment was applied in seven weekly sprays from 18 May to 4 July. Leaf samples were harvested on 28 June, and all heads were harvested on 28 June, 5 July, and 7 July.

IV. RESULTS

A. Greenhouse Experiment (1988)

1. Experiment one: Mo nutrition in sand culture (1988). Broccoli plants grew well when 0 to 100 μM Mo was added to the nutrient solution, but 1000 μM Mo was observed to be toxic to the plants. None of the plants grown in 1000 μm Mo reached maturity and no weight measurements were taken. There were no significant differences in root and head fresh weights and root, shoot, and head dry weights. However, a significant quadratic response to Mo for shoot weight suggests that a Mo concentration near 1 to 10 μM Mo is optimal for shoot growth (Table 4).

A quadratic response to Mo concentration for days to harvest (Table 5) suggests that growth should be most rapid at an intermediate Mo concentration in the nutrient solution. However, the disparity in time to harvest was very small, ranging from 66 days at 1.0 and 10 μM Mo to 70 days for no added Mo, and most of the effect on growth appears to be a reduction in growth rate with 100 μM Mo in the nutrient solution.

Broccoli plants readily took up Mo from the nutrient solution. For each tenfold increase in nutrient solution

Mo, from 0.1 to 100 μM, tissue Mo increased six to twelve fold (Table 6).

All broccoli plants appeared normal except those grown in a 1000 μM Mo solution. Plants grown in a 1000 μM solution germinated normally, but the cotyledons were darker green than plants grown at other Mo concentrations. Most plants died after producing one true leaf. The true leaves were pale blue-green, but no blue granules, which were seen on cauliflower (Agarwala, 1950), were noticed.

Table 4. The effect of Mo concentration in the nutrient solution on fresh weight of broccoli plants grown in the greenhouse, 1988.

Molybdenum added (μM)	Fresh wt (g)[z]		
	Shoot wt	Head wt[y]	Total wt
None	929	379	1308
0.1	926	412	1339
1.0	985	412	1396
10	980	332	1312
100	830	397	1227
F-test	***	NS	NS
LSD 0.001	155		
Linear[x]	NS	NS	NS
Quadratic[x]	**	NS	*
Cubic[x]	*	*	NS
CV (%)	8	16	9

[z]Figures are means for 6 plants.

[y]Above ground portion excluding the head.

[x]The no Mo added treatment was assigned a Mo concentration of 0.001 μM to facilitate analysis based on $\log_{10}$ added Mo.

NS,*,**,***Non significant and significant at the 5, 1, and 0.1% levels, respectively.

Table 5. The effect of Mo concentration in the nutrient solution on broccoli maturity in the greenhouse, 1988.

Molybdenum added (μM)	Days to Harvest[z]
None	70
0.1	66
1.0	67
10	66
100	68
F-test	*
LSD 0.05	2
Linear[y]	NS
Quadratic[y]	**
Cubic[y]	NS
CV (%)	3

[z]Figures are means for 6 plants.

[y]The no Mo added treatment was assigned a Mo concentration of 0.001 μM to facilitate analysis based on $\log_{10}$ added Mo.

NS,*,**Non significant and significant at the 5% and 1% levels, respectively.

Table 6. The effect of Mo concentration in the nutrient solution on Mo concentration of recently expanded leaves in the greenhouse, 1988.

	Mo (ppm, dry wt basis)[z]	
Molybdenum added (μM)	11 May	At head harvest 26 May through 6 June
None	1	1
0.1	4	2
1.0	23	24
10	180	220
100	1400	1800

[z]Figures are means for 6 plants.

B. Field Experiments

1. Experiment one: Soil and foliar-applied Mo (Spring 1986). Fresh weight yield of broccoli heads was not affected by any of the Mo treatments (Table 7). Leaf Mo content was higher with two 300 $g \cdot ha^{-1}$ foliar applications of Mo and 4.1 $kg \cdot ha^{-1}$ ppi Mo (Table 7). The high coefficient of variability indicates that leaf Mo concentration was highly variable (Table 7).

2. Experiment two: Soil and foliar-applied Mo (Fall 1986). Fresh weight yield of broccoli heads was higher as a result of 4.1 $kg \cdot ha^{-1}$ ppi Mo applications as compared to the controls (Table 8). Leaf Mo concentration was higher in plots receiving 9 weekly foliar applications of 150 and 300 $g \cdot ha^{-1}$ Mo, and 4.1 $kg \cdot ha^{-1}$ Mo ppi than the controls (Table 8).

3. Experiment three: Soil and foliar-applied Mo (Summer 1987). The fresh weight yield of broccoli heads was the highest for plants treated with 2.2 $kg \cdot ha^{-1}$ Mo. Yield was lower when a 10 mM pretransplant drench was applied (Table 9). Only foliar-applied 220 $g \cdot ha^{-1}$ Mo resulted in significantly higher concentrations of Mo in the leaves (Table 9).

4. Experiment four: Soil and foliar-applied Mo (Fall 1987). None of the Mo applications significantly affected broccoli yield compared to the control (Table 10). The concentration of Mo was higher in the leaves of plants from

plots treated with 2.2 $kg \cdot ha^{-1}$ Mo ppi and 6 weekly 220 $g \cdot ha^{-1}$ foliar Mo applications than the controls (Table 10).

5. Experiment five: Soil and foliar-applied Mo (Summer 1988). None of the Mo treatments significantly affected the weight of broccoli heads (Table 11). Leaf Mo concentration was higher than the controls after 5 weekly 220 $g \cdot ha^{-1}$ foliar Mo applications and a 2.2 $kg \cdot ha^{-1}$ ppi Mo application. The high coefficient of variability indicates that leaf Mo concentration was highly variable (Table 7).

Table 7. The effect of Mo application on broccoli yield and recently expanded leaf Mo concentration in the field, Spring 1986.

Amount and method of actual Mo application	Head fresh wt (g)[z]	Mo (ppm)[y]
Control	400	1
150 $g \cdot ha^{-1}$ Mo foliar spray[x]	403	7
300 $g \cdot ha^{-1}$ Mo foliar spray[x]	400	24
4.1 $kg \cdot ha^{-1}$ Mo ppi	410	32
F-test	NS	**
LSD 0.01		23
CV (%)	10	47

[z]Figures are means of 10 heads per plot.

[y]Dry wt basis.

[x]Two applications.

NS,**Non significant and significant at the 1% level, respectively.

Table 8. The effect of Mo application on broccoli yield and recently expanded leaf Mo concentration in the field, Fall 1986.

Amount and method of actual Mo application	Head fresh wt (g)[z]	Mo (ppm)[y]
Control	271	1
150 g.ha^{-1} Mo foliar spray[x]	279	22
300 g.ha^{-1} Mo foliar spray[x]	281	60
4.1 kg.ha^{-1} Mo ppi	348	38
F-test	**	***
LSD 0.05	44	16
CV (%)	7	27

[z]Figures are means for 10 heads.

[y]Dry wt basis.

[x]Nine weekly applications.

,*Significant at the 1 and 0.1% level, respectively.

Table 9. The effect of Mo application on broccoli yield and recently expanded leaf Mo concentration in the field, Summer 1987.

Amount and method of actual Mo application	Head fresh wt (g)[z]	Mo (ppm)[y]
Control	279	1
10 mM Mo pretransplant drench	234	2
220 $g \cdot ha^{-1}$ Mo foliar spray[x]	301	100
2.2 $kg \cdot ha^{-1}$ Mo ppi	323	1
F-test	**	***
LSD 0.05	37	6
CV (%)	6	12

[z]Figures are means for all heads (approximately 25) in each plot.

[y]Dry wt basis.

[x]Five weekly applications.

,*Significant at the 1 and 0.1 % level, respectively.

Table 10. The effect of Mo application on broccoli yield and recently expanded leaf Mo concentration in the field, Fall 1987.

Amount and method of actual Mo application	Head fresh wt (g)[z]	Mo (ppm)[y]
Control	489	1
5 mM Mo pretransplant drench	403	2
220 $g \cdot ha^{-1}$ Mo foliar spray[x]	443	43
2.2 $kg \cdot ha^{-1}$ Mo ppi	517	5
F-test	S	***
LSD 0.1 0.5	70	4
CV (%)	10	16

[z]Figures are means for all heads (approximately 25) in each plot.

[y]Dry wt basis.

[x]Six weekly applications.

S,***Significant at the 10 and 0.1 % level, respectively.

Table 11. The effect of Mo application on broccoli yield and recently expanded leaf Mo concentration in the field, Summer 1988.

Amount and method of actual Mo application	Head fresh wt (g)[z]	Mo (ppm)[y]
Control	480	4
5 mM Mo pretransplant root dip	545	2
220 $g \cdot ha^{-1}$ Mo foliar spray[x]	522	57
2.2 $kg \cdot ha^{-1}$ Mo ppi	323	56
F-test	NS	**
LSD 0.01		40
CV (%)	10	45

[z]Figures are means for all heads (approximately 25) in each plot.

[y]Dry wt basis.

[x]Five weekly applications.

NS,**Non significant and significant at the 1% level, respectively.

V. DISCUSSION

Of the Mo levels used in the greenhouse, 1.0 μM produced the highest yield. Leaves from these plants averaged 23 to 24 ppm Mo depending on the harvest date. In the field, no relationship between Mo concentration in the leaves and yield was apparent. However, there was a yield response to Mo application in several experiments. The application method appears to be an important factor in the effectiveness of Mo application on broccoli. Both ppi and foliar-applied Mo were effective in achieving enhanced leaf Mo concentration, but only ppi Mo induced higher yields.

The two experiments in which no significant yield differences were observed had very high coefficients of variation for Mo concentration (Tables 7 and 11). It is possible that in these areas, the distribution of Mo already present in the soil was uneven. Molybdenum deficiency can be scattered unevenly, sometimes giving a field a mottled green and yellow appearance (Soil Science, 1956). It may be that natural variation in the soil contributed to the lack of yield response in these experiments.

In all but one of the field experiments, plots receiving ppi Mo had the highest yield of broccoli heads (Tables 7, 8, 9, and 10). It may be that ppi treatments

were superior because they provided a moderate, steady supply of Mo available throughout the season.

Drenching the plants with an Mo solution before transplanting reduced yield (Table 9). Probably the Mo solution was too concentrated and caused slight phytotoxicity. Within a few minutes after the drench treatment, leaf color changed to a lighter green color similar to color of true leaves on plants grown in a 1000 μM Mo solution in the greenhouse.

Foliar applications may have resulted in a widely fluctuating Mo concentration in the plants, particularly in leaves. After foliar applications of Mo, the Mo concentration in the leaves may have risen rapidly and then declined. Compared to Mo concentrations used in the greenhouse, the foliar applications were quite concentrated. The 150, 220, and 300 $g \cdot ha^{-1}$ foliar Mo applications are equivalent to 4,000 μM, 6,000 μM, and 8,000 μM Mo, respectively. Plants grown in the greenhouse using 1,000 μM Mo solution eventually died. Plants receiving foliar-applied Mo may have suffered slight injury.

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Chapter 4

THE EFFECT OF ADJUVANTS ON FOLIAR UPTAKE OF CALCIUM BY CAULIFLOWER AND MOLYBDENUM BY BROCCOLI

I. ABSTRACT

Several adjuvants - a 6 molar linear alcohol (Flo Mo 6-T), a 4.5 molar ethoxylated alkyl phenol (Flo Mo S-45), a 10 molar ethoxylated alkyl phenol (Flo Mo S-100), a proprietary mixture of alkyl aryl polyethylene glycols (Triton AG-98), a silicon based surfactant (Silwet L-77), and a crop oil concentrate of 17% mono and diesters of omega hydroxyl oxyethylene in a light paraffinic distillate, orderless aliphatic solvent (Herbimax) - were added to a 240 mM Calcium (Ca) solution which was foliar-applied to cauliflower (*Brassica oleracea* var. *botrytis*) plants or 6 mM Molybdenum (Mo) solution which was foliar-applied to broccoli (*Brassica oleracea* var. *italica*) plants. After 2 days leaves were harvested and later analyzed for dry weight Ca and Mo content, respectively.

No increase in Ca uptake was detected when adjuvants were used. All of the adjuvants used increased Mo uptake at 70% relative humidity (RH). Silwet L-77 always resulted in the greatest Mo uptake. Only Silwet L-77 enhanced Mo uptake at 18% RH.

II. INTRODUCTION

Foliar application can be an effective means of applying nutrients. Small amounts of nutrients often give good response because uptake begins immediately. In some cases, broccoli plants suffering from whiptail recover after a foliar application of molybdenum (Mo) (Plant, 1950). However, foliar fertilization often gives inconsistent results (Neumann, 1982). Foliar uptake of chemicals by plants varies considerably, depending on many factors. Therefore, it is difficult to deliver a precise dose. Adjuvants may help reduce some adverse environmental effects and improve uptake.

III. MATERIALS AND METHODS

A. Introduction

Experiments were conducted in the Plant Science Greenhouse at Michigan State University, East Lansing, Michigan to investigate the effect of various adjuvants on foliar Ca uptake by 'White Fox' cauliflower and of Mo uptake by 'Packman' broccoli.

B. Treatments Applied

Calcium chloride ($CaCl_2$) solutions containing 240 mM Ca or sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$) solutions containing 6 mM Mo (Tables 1 and 2)) were applied with several additives, to cauliflower and broccoli foliage, respectively. All treatments were applied with a hand held, CO_2 charged sprayer at 200 kPa with a 9508E spray tip delivering 370 liters$\cdot ha^{-1}$. Deionized water was used as a carrier for all treatments.

The nonionic surfactants chosen included a 6 molar linear alcohol (Flo Mo 6-T), a 4.5 molar ethoxylated alkyl phenol (Flo Mo S-45), a 10 molar ethoxylated alkyl phenol (Flo Mo S-100), a proprietary mixture of alkyl aryl polyethylene glycols (Triton AG-98), and a silicon based surfactant (Silwet L-77).

C. Tissue Analysis

After harvest, tissue samples were washed in deionized water, then in 0.15 N hydrochloric acid (HCl), followed by two deionized water rinses. The samples were forced air dried at 70°C and ground in a Wiley mill to pass through a 1.3 mm screen. The ground tissue was redried at 70°C for at least 24 hours and weighed for ashing.

Cauliflower leaf tissue was prepared for Ca analysis by digesting 0.1 g of tissue in 0.5 ml of 30% hydrogen peroxide (H_2O_2) and 1 ml of perchloric acid ($HClO_4$) for 5 min on a Tecator Digestion System 40, 1016 digester at 300°C. The 100 ml digestion tubes were then removed from the digestion

block and 1 ml of 30% H_2O_2 was added to each sample. Then the digestion tubes were returned to the digestion block for 30 to 45 min. After the digestion tubes were filled one-half to three-quarters full with deionized water, the samples were reheated slightly to dissolve crystals that formed when the samples cooled. The digestion procedure described above was adapted from Adler and Wilcox (1985).

Five percent weight for volume ($g \cdot ml^{-1}$) lanthanum (La) was added to equalize ionization among the samples and standards. Lanthanum also acts as a releasing agent, preventing the formation of Ca compounds which are not atomized by a C_2H_2 flame. The La stock solution contained 180 ml of concentrated $HCl \cdot liter^{-1}$ and 117 g of lanthanum oxide (La_2O_3)$\cdot liter^{-1}$. It was prepared by mixing lanthanum oxide (La_2O_3) with a small amount of deionized water and adding HCl to dissolve the La_2O_3 before bringing the solution to volume with deionized water.

Broccoli leaf tissue was dry ashed for Mo analysis. The tissue was weighed into Coors porcelain crucibles using a Mettler PC 440 electronic balance and ashed at 550°C for 8 hours in a muffle furnace. The ashed tissue was then dissolved in 10 ml of 1.5 N HCl. The samples were rinsed out of the crucibles and brought up to volume with 1.5 N HCl. The amount of tissue and the volume of solution were varied to keep the Mo concentration within an acceptable range for analysis. Prior to analysis, the samples were

filtered through Schleicer & Schuell number 588 analytical filter paper.

The samples were analyzed with an Instrumentation Laboratory Video 12 atomic absorption - atomic emission spectrophotometer. Calcium was analyzed at a wavelength of 422.7 nm and a bandwidth of 1.0 nm by acetylene (C_2H_2) flame, atomic absorption spectrophotometry with an Instrumentation Laboratory Ca hollow cathode-Ca lamp. Molybdenum was analyzed at a wavelength of 313.3 nm and a bandwidth of 0.5 nm by nitrous oxide-acetylene (NO_2-C_2H_2) flame, atomic absorption spectrophotometry with an Instrumentation Laboratory, Mo hollow cathode lamp. All samples were aspirated at a 6 $ml \cdot min^{-1}$ flow rate.

D. Statistical Analysis

Analysis of variance was used to evaluate the data. LSD values were computed for the appropriate significance level. The statistical analyses were performed using MSTAT.

E. Uptake of Calcium by Cauliflower.

1. Foliar absorption of Ca under cloudy conditions (1987). Cauliflower seeds were planted in 96-cell flats on 10 March 1987. The cells held about 30 cc of media, were 5.5 by 4 cm wide at the top and 4 cm high. The plants were transplanted to 12 cm high clay pots with an inside diameter of 13 cm at the top. The pots were filled with about 750 cc of a commercial peat-perlite-vermiculite media on 13 April. The plants were grown under natural lighting which provided

about 12 $mol \cdot m^{-2} \cdot day^{-1}$ photosynthetic photon flux (PPF). The greenhouse was heated to 24°C, but the temperature reached 32°C on warm, sunny days.

Treatments were applied in the greenhouse on 17 May (Table 1). A completely randomized design with 8 replications (single plants) was used. The air temperature was 24°C and the relative humidity (RH) was 70% at treatment. The sky was cloudy.

Leaves were harvested from each plant on 19 May, 48 hours after application, for Ca analysis. All of the fully-expanded and nearly fully-expanded leaves were collected from each plant and combined to make one sample.

Table 1. List of treatments applied to cauliflower plants.

1. Deionized water control.
2. 240 mM Ca without additives.
3. 240 mM Ca + 1% (v/v) Herbimax crop oil concentrate.[z]
4. 240 mM Ca + 0.25% (v/v) DeSoto Flo Mo 6-T.[y]
5. 240 mM Ca + 0.25% (v/v) DeSoto Flo Mo S-45.[y]
6. 240 mM Ca + 0.25% (v/v) DeSoto Flo Mo S-100.[y]
7. 240 mM Ca + 0.25% (v/v) Triton AG-98.[x]
8. 240 mM Ca + 0.25% (v/v) Union Carbide Silwet L-77.[w]

[z]Loveland Industries, Greeley, Colo.

[y]DeSoto, Fort Worth, Tex.

[x]Rohm and Haas, Philadelphia, Pa.

[w]Union Carbide, Danbury, Conn.

2. Foliar absorption of Ca under partial sunshine (1987). Seeds were planted on 15 June, and the seedlings were transplanted to pots on 27 July. Except for the first three weeks after seeding, the plants were grown on outside benches.

A completely randomized design with 9 replications (single plants) was used. Heads were beginning to develop when the treatments were applied outside the greenhouse on 6 September. There was hazy sunshine with a 28°C air temperature and 70% RH at treatment. After the treatments were applied the plants were moved inside the greenhouse.

Leaves 11 through 14 were harvested from each plant on 8 September. Leaves and leaf scars were counted beginning at the base of the plant to determine which leaves to harvest.

3. Foliar absorption of Ca under sunny conditions (1988). Seeds were planted on 13 Apr, and the seedlings were transplanted to pots on 6 May. The plants were grown under natural lighting which provided about 12 $mol \cdot m^{-2} \cdot day^{-1}$ PPF. The greenhouse was heated to 24°C.

A completely randomized design with 10 replications (single plants) was used. Treatments were applied on 5 June. The plants were sprayed outside then put back in the greenhouse after the spray solution dried on the leaves. The sky was clear with a 29°C air temperature and 18% RH.

Leaves 5 through 9 were harvested from each plant on 8 September. Leaves and leaf scars were counted beginning at the base of the plant to determine which leaves to harvest.

F. Uptake of Molybdenum by Broccoli.

1. Foliar absorption of Mo under cloudy conditions (1987). Broccoli seeds were planted in 96-cell flats on 10 March 1987. These cells are 5.5 by 4 cm wide at the top, 4 cm high, and hold approximately 30 cc of media. The plants were transplanted to pots which were 13 cm in diameter at the top and 12 cm high. These pots were filled with about 750 cc of a commercial peat-perlite-vermiculite media on 13 April. The plants were grown under natural lighting which provided about 12 $mol \cdot m^{-2} \cdot day^{-1}$ photosynthetic photon flux (PPF). The greenhouse was heated to 24°C, but the temperature reached 32°C on warm, sunny days.

Treatments were applied in the greenhouse on 17 May (Table 2). A completely randomized design with 8 replications (single plants) was used. The air temperature was 24°C and the relative humidity (RH) was 70% at treatment. The sky was cloudy.

Leaves were harvested from each plant on 19 May for Mo analysis. All of the fully-expanded and nearly fully-expanded leaves were collected from each plant. The leaves from each plant were combined to make one sample from each plant.

Table 2. List of treatments applied to broccoli plants.

1. Deionized water control.
2. 6 mM[z] Mo without additives.
3. 6 mM[z] Mo + 1% (v/v) Herbimax crop oil concentrate.[y]
4. 6 mM[z] Mo + 0.25% (v/v) DeSoto Flo Mo 6-T.[x]
5. 6 mM[z] Mo + 0.25% (v/v) DeSoto Flo Mo S-45.[x]
6. 6 mM[z] Mo + 0.25% (v/v) DeSoto Flo Mo S-100.[x]
7. 6 mM[z] Mo + 0.25% (v/v) Triton AG-98.[w]
8. 6 mM[z] Mo + 0.25% (v/v) Union Carbide Silwet L-77.[v]

[z]600 ppm.

[y]Loveland Industries, Greeley, Colo.

[x]DeSoto, Fort Worth, Tex.

[w]Rohm and Haas, Philadelphia, Pa.

[v]Union Carbide, Danbury, Conn.

2. Foliar absorption of Mo under partial sunshine (1987). Seeds were planted on 15 June, and the seedlings were transplanted to pots on July 27. Except for the first three weeks after seeding, the plants were grown on outside benches.

A completely randomized design with 10 replications (single plants) was used. Heads were beginning to develop when the treatments (Table 2) were applied outside the greenhouse on 6 September. There was hazy sunshine with a 28°C air temperature and 70% RH at treatment. After the treatments were applied the plants were moved inside the greenhouse.

Leaves 11 through 14 were harvested from each plant on 8 September. Leaves and leaf scars were counted beginning at the base of the plant to determine which leaves to harvest.

3. Foliar absorption of Mo under sunny conditions (1988). Seeds were planted on 13 Apr, and the seedlings were transplanted to pots on 6 May. The plants were grown under natural lighting which provided about 12 $mol \cdot m^{-2} \cdot day^{-1}$ PPF. The greenhouse was heated to 24°C.

Treatments (Table 2) were applied on 5 June. The plants were sprayed outside then put back in the greenhouse after the spray solution dried. The sky was clear with a 29°C air temperature and 18% RH. A randomized complete block design with 10 replications was used. Each block

consisted of one plant for each treatment. The plants were blocked according to their position on the greenhouse bench.

On 7 June, leaves 5 through 9 were harvested for Mo analysis.

IV. RESULTS AND DISCUSSION

A. Uptake of Calcium by Cauliflower.

The adjuvants had no detectable effect on the absorption of Ca by leaves from a foliar-applied solution (Table 3).

Table 3. The effect of adjuvants on Ca uptake by cauliflower as shown by Ca removed from leaves after 2 days.

Treatment	Leaf dry wt Ca (%)			
	Cloudy 24°C 70% RH	Partial sunshine 28°C 70% RH	Sunshine 29°C 18% RH	avg
Deionized water	0.9	1.0	1.1	1.0
240 mM Ca	0.9	0.8	1.1	0.9
240 mM Ca + Herbimax	1.0	0.7	1.1	0.9
240 mM Ca + 6-T	1.1	0.8	1.0	1.0
240 mM Ca + S-45	1.0	0.8	1.0	0.9
240 mM Ca + S-100	1.1	1.1	1.0	1.0
240 mM Ca + AG-98	1.1	0.8	1.2	1.0
240 mM Ca + L-77	1.1	0.7	1.1	0.9
F-test	NS	NS	NS	
CV (%)	19	29	25	

[NS]Non significant.

B. Uptake of Molybdenum by Broccoli.

Adding adjuvants to the Mo solution increased Mo uptake by broccoli. Silwet L-77 enhanced uptake more, and appeared to be less affected by environmental conditions than the other adjuvants (Table 4).

Solutions containing Herbimax took much longer to dry than solutions containing any of the other adjuvants. The long drying time may explain why net uptake by leaf tissue was relatively high. Uptake from solutions can be much faster than from dry deposits (Stevens et al., 1988).

Silwet L-77 probably enhance uptake because it lowers surface tension greatly (Union Carbide, 1980). The low surface tension could increase wetting of these waxy leaves, allowing better contact between the Mo solution and the leaves.

Small lesions developed on the leaves of a few plants in the first experiment. These lesions were observed during the first experiment, particularly in leaf depressions where solutions collected. The most injury occurred on plants sprayed with Mo solution containing Flo Mo 6-T or Flo Mo S-100. No injury was found on plants sprayed with water only, Mo solution without surfactant, or Mo solution with Silwet L-77 or Herbimax.

The environmental conditions appeared to have large effect on Mo uptake. Generally, under cloudy, humid conditions Mo uptake was greatest; under humid, sunny

conditions it was intermediate; and under dry, sunny conditions, uptake was least. Only Silwet L-77 significantly increased Mo uptake compared to no surfactant when the RH was low.

The results have practical significance for foliar application of Mo. Because Silwet L-77 increased uptake greatly, it could increase the efficiency of foliar-applied Mo, reducing the Amount of Na_2MoO_4 required. Silwet L-77 was also more reliable, allowing greater control over the amount of Mo taken up by the plant.

Table 4. The effect of adjuvants on Mo uptake by broccoli as shown by Mo recovered from leaves after 2 days.

Treatment	Leaf dry wt Mo (ppm)			
	Cloudy 24°C 70% RH	Partial sunshine 28°C 70% RH	Sunshine 29°C 18% RH	avg
Deionized water	6	6	14	9
6 mM[z] Mo	25	17	42	28
6 mM[z] Mo + Herbimax	92	99	49	80
6 mM[z] Mo + 6-T	121	52	23	66
6 mM[z] Mo + S-45	81	44	22	49
6 mM[z] Mo + S-100	102	64	24	63
6 mM[z] Mo + AG-98	92	62	29	61
6 mM[z] Mo + L-77	189	153	113	152
F-test	***	***	***	
LSD 0.001	58	42	23	
CV (%)	38	44	38	

[z]600 ppm.

***Significant at the 0.1% level.

V. LITERATURE CITED

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SUMMARY AND CONCLUSIONS

In the review of literature on calcium (Ca), it was found that even though insufficient Ca in rapidly growing tissues leads to Ca deficiency symptoms in many plants, there is not a simple relationship between Ca available in the soil and Ca deficiency symptoms in the plant. Many factors affect Ca uptake, translocation, and the occurrence of Ca deficiency symptoms. However, Ca availability is important.

In greenhouse experiments, it was found that cauliflower tipburn and curd quality could be controlled by changing the Ca concentration in the nutrient solution. Field experiments have shown that foliar-applied Ca can reduce tipburn, and that applying Ca to the soil may, under some conditions, reduce tipburn. As soil Ca increased tipburn tended to decrease.

Weekly application of foliar-applied Ca beginning approximately 45 days after transplanting should provide some control of tipburn under field conditions. Foliar applications probably need to begin earlier on a early season variety than on a late season variety. The date to begin applications should be adjusted to fit the variety being grown.

In the review of literature, it was found that cauliflower tolerates a wide range of available Mo. In the greenhouse, broccoli tolerated a wide range of media-available and tissue Mo. Growth was good when from 0 to 100 μM Mo was added to the nutrient solution. This resulted in from 1 to almost 2,000 ppm Mo in dry leaf tissue. Plants grown in 1000 μM Mo did not reach maturity.

In field experiments, broccoli leaf Mo was increased by foliar and preplant incorporated (ppi) Mo, but only ppi Mo increased yield. This method of Mo application may provide a moderate, steady supply of Mo throughout the growing period. Molybdenum should be applied to the soil when it is suspected that the soil is not providing an adequate supply of Mo to broccoli plants.

In the review of literature on adjuvants, it was found that foliar uptake of chemicals is controlled by many factors. Although many of these factors have been researched, it is still difficult to predict how much of a chemical will be absorbed by leaves.

Data from greenhouse experiments show that an organosilicone surfactant (Silwet L-77) increased Mo uptake by broccoli leaves more than several other adjuvants. When the relative humidity was low only Silwet L-77 increased Mo uptake. This is important, since it makes uptake more predictable. Foliar uptake needs to be reliable and predictable in order to consistently deliver a controlled amount of Mo to the plants.

GLOSSARY

GLOSSARY

Crop Oil Concentrate An emulsifiable oil that provides a lipophilic moiety and increases droplet drying time.

Curd Leaves Pale green leaves surrounding and extending about 6 to 8 cm above the curd.

Flo Mo 6-T A 6 molar ethoxylate of tridecal-linear alcohol 100%. DeSoto, Fort Worth, Texas.

Flo Mo S-100 A 10 molar ethoxylate of octylphenol 100%. DeSoto, Fort Worth, Texas.

Flo Mo S-45 A 4.5 molar ethoxylate of octylphenol 100%. DeSoto, Fort Worth, Texas.

Herbimax Mono and diesters of omega hydroxyl oxyethylene 17%; in a light paraffinic distillate, orderless aliphatic solvent. Loveland Industries, Greeley, Colorado.

Recently Expanded Leaf The youngest leaf on the plant that will not increase in size. In general, especially when cauliflower and broccoli plants are young, it is the largest leaf on the plant. In 1987, and 1988, 'White Fox' cauliflower experiments, the leaf that was just beginning to tip from a vertical to a horizontal position was harvested from older (second leaf harvest) plants.

Silwet L-77 Oxyethylene methyl siloxane 100%. Union Carbide, Danbury, Connecticut.

Soil Calcium Soil Ca was analyzed using a standard ammonium acetate extraction method described on page 88.

Triton AG-98 Alkyl Aryl polyoxyethylene glycols 80%. Rohm and Haas, Philadelphia, Pennsylvania.

APPENDIX

FARM WEATHER DATA

APPENDIX

Table 1. July 1985 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
July	1	26	11	
	2	26	14	
	3	29	12	
	4	28	12	
	5	30	15	7
	6	25	13	3
	7	23	9	
	8	26	21	
	9	32	17	
	10	28	17	
	11	26	13	
	12	25	12	1
	13	30	16	
	14	31	18	9
	15	30	19	
	16	27	13	8
	17	25	9	
	18	26	11	
	19	28	17	
	20	27	18	16
	21	27	17	
	22	26	13	
	23	23	6	
	24	25	9	
	25	28	21	
	26	31	15	7
	27	25	10	
	28	27	13	
	29	29	16	
	30	30	14	
	31	22	15	1

APPENDIX

Table 2. August 1985 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
August	1	16	10	2
	2	25	7	
	3	25	8	
	4	28	11	
	5	30	17	9
	6	22	17	11
	7	26	17	1
	8	27	12	2
	9	29	14	
	10	31	17	
	11	26	11	
	12	24	10	
	13	28	17	
	14	28	15	
	15	28	16	27
	16	20	10	2
	17	26	10	
	18	28	17	1
	19	25	10	13
	20	20	10	
	21	18	12	
	22	22	9	
	23	22	10	
	24	25	17	2
	25	18	14	24
	26	25	15	
	27	25	14	3
	28	25	16	
	29	26	17	
	30	26	17	7
	31	20	11	T

APPENDIX

Table 3. September 1985 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date	High (°C)	Low (°C)	Precipitation (mm)
September 1	23	11	
2	25	16	T
3	26	18	
4	30	21	
5	27	20	2
6	26	20	14
7	28	22	9
8	32	20	18
9	31	19	14
10	26	15	2
11	17	7	T
12	18	6	
13	15	2	
14	16	2	
15	19	3	
16	21	6	
17	23	9	
18	24	15	T
19	23	15	T
20	27	15	
21	28	11	
22	15	11	T
23	26	14	
24	26	7	23
25	15	1	
26	15	8	4
27	12	2	
28	16	5	
29	21	6	
30	22	10	

APPENDIX

Table 4. October 1985 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
October	1	16	6	6
	2	10	2	
	3	15	-1	
	4	17	-1	
	5	15	6	11
	6	15	2	1
	7	11	1	T
	8	19	4	
	9	18	12	8
	10	18	13	T
	11	15	3	6
	12	13	3	1
	13	21	8	9
	14	16	6	1
	15	17	9	6
	16	16	5	
	17	11	29	
	18	17	-1	
	19	17	11	55
	20	15	8	1
	21	14	5	T
	22	15	5	
	23	13	10	
	24	17	12	18
	25	20	4	1
	26	16	2	
	27	20	6	2
	28	15	0	
	29	11	0	
	30	12	1	
	31	11	1	

APPENDIX

Table 5. May 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
May	1	15	12	
	2	10	-1	
	3	13	-1	
	4	21	1	
	5	26	15	
	6	27	18	12
	7	22	12	
	8	18	5	
	9	19	6	
	10	23	5	
	11	25	6	
	12	19	9	
	13	26	8	
	14	23	13	2
	15	23	10	8
	16	18	15	26
	17	27	11	24
	18	15	15	17
	19	8	8	7
	20	8	6	2
	21	11	7	4
	22	13	7	1
	23	18	9	
	24	18	9	
	25	22	10	
	26	26	12	
	27	18	16	10
	28	26	13	
	29	28	12	
	30	27	15	
	31	29	16	

APPENDIX

Table 6. June 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
June	1	27	18	1
	2	16	6	
	3	23	2	
	4	28	7	57
	5	18	13	1
	6	19	14	
	7	26	16	2
	8	26	16	
	9	25	7	
	10	23	11	1
	11	27	20	62
	12	21	17	T
	13	24	12	
	14	23	10	9
	15	26	14	3
	16	28	19	
	17	20	7	
	18	24	7	
	19	26	15	18
	20	22	13	
	21	28	11	
	22	29	19	2
	23	27	15	2
	24	17	12	
	25	22	5	
	26	25	11	6
	27	28	21	6
	28	26	20	
	29	27	12	
	30	19	13	3

APPENDIX

Table 7. August 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
August	1	27	14	
	2	26	15	8
	3	24	11	
	4	27	12	
	5	27	12	
	6	23	17	12
	7	24	17	T
	8	26	15	
	9	27	15	
	10	22	16	4
	11	22	9	
	12	23	6	
	13	25	8	
	14	25	11	1
	15	27	15	
	16	28	18	
	17	30	15	
	18	27	14	
	19	26	12	
	20	27	11	
	21	29	13	
	22	29	13	
	23	22	20	17
	24	23	11	
	25	24	10	
	26	23	15	57
	27	15	10	
	28	17	3	
	29	20	5	
	30	23	4	
	31	24	7	

APPENDIX

Table 8. September 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date	High (°C)	Low (°C)	Precipitation (mm)
September 1	26	8	
2	26	10	
3	28	12	6
4	26	18	
5	21	11	
6	18	5	
7	16	2	
8	19	2	
9	22	3	3
10	24	12	8
11	22	16	24
12	18	14	
13	20	8	
14	18	5	1
15	23	10	2
16	15	2	
17	20	1	8
18	17	11	
19	20	12	1
20	20	17	
21	19	13	29
22	28	14	33
23	22	16	
24	24	13	23
25	28	16	
26	26	21	25
27	26	16	1
28	26	16	15
29	27	17	37
30	21	18	6

APPENDIX

Table 9. October 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
October	1	21	12	6
	2	14	11	14
	3	18	11	2
	4	20	13	15
	5	14	7	7
	6	16	2	3
	7	11	1	
	8	17	2	
	9	20	5	3
	10	10	-1	
	11	12	0	
	12	20	1	
	13	18	8	2
	14	10	5	9
	15	6	2	1
	16	8	1	
	17	7	3	1
	18	10	-2	
	19	13	-1	
	20	16	-1	
	21	18	2	
	22	21	7	
	23	21	10	
	24	20	7	
	25	12	5	
	26	12	5	5
	27	15	10	1
	28	13	4	T
	29	19	5	
	30	12	-1	T
	31	10	0	

APPENDIX

Table 10. November 1986 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
November	1	17	4	
	2	13	1	3
	3	7	-1	
	4	8	-1	
	5	4	-3	
	6	9	-2	
	7	13	1	
	8	12	6	1
	9	18	3	
	10	4	-5	
	11	4	-5	
	12	1	-7	
	13	1	-12	1
	14	-6	-12	
	15	-1	-10	
	16	1	-1	
	17	5	-2	
	18	10	-1	
	19	-1	-12	1
	20	1	-11	1
	21	2	-1	8
	22	2	-2	
	23	7	-2	1
	24	5	0	2
	25	1	-3	
	26	11	-2	3
	27	3	-4	12
	28	6	-5	
	29	6	-1	
	30	8	-1	

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Table 11. May 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
May	1	15	0	
	2	18	8	5
	3	15	3	T
	4	17	0	
	5	19	-1	
	6	21	2	
	7	19	7	1
	8	21	2	
	9	27	8	T
	10	29	16	
	11	28	18	11
	12	16	5	
	13	23	1	
	14	28	11	T
	15	18	6	
	16	25	5	
	17	29	12	2
	18	15	12	4
	19	15	10	9
	20	23	13	
	21	31	13	
	22	27	18	
	23	16	12	
	24	16	7	
	25	21	8	1
	26	30	10	
	27	32	16	
	28	32	19	
	29	32	20	
	30	32	21	5
	31	29	18	

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Table 12. June 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
June	1	26	17	
	2	27	16	10
	3	25	16	
	4	22	10	
	5	26	7	6
	6	26	9	5
	7	31	16	
	8	26	17	5
	9	20	8	
	10	23	11	
	11	26	11	6
	12	30	14	
	13	30	15	
	14	35	15	
	15	30	16	
	16	32	10	
	17	31	13	
	18	34	13	
	19	35	14	
	20	28	14	
	21	27	20	27
	22	21	17	
	23	28	16	
	24	31	15	
	25	31	17	1
	26	25	15	1
	27	20	13	
	28	27	10	
	29	27	14	4
	30	18	17	1

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Table 13. July 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
July	1	23	14	
	2	27	12	
	3	28	15	
	4	26	15	
	5	27	14	5
	6	29	17	
	7	30	20	
	8	32	21	
	9	31	18	24
	10	31	18	3
	11	32	20	
	12	33	22	
	13	30	20	2
	14	21	11	
	15	16	5	4
	16	26	9	
	17	30	12	
	18	32	16	
	19	33	18	
	20	35	23	1
	21	32	18	
	22	33	17	
	23	33	20	
	24	33	22	14
	25	31	21	14
	26	30	20	
	27	28	15	
	28	28	12	
	29	31	15	
	30	33	17	
	31	32	17	1

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Table 14. August 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
August	1	26	19	2
	2	35	20	
	3	33	18	5
	4	30	20	
	5	25	13	
	6	29	11	
	7	31	15	
	8	22	16	13
	9	28	16	1
	10	26	16	
	11	27	12	
	12	29	12	
	13	32	15	
	14	28	17	6.6
	15	33	20	
	16	33	22	7
	17	27	18	
	18	26	12	T
	19	25	13	
	20	27	8	
	21	28	13	45
	22	23	17	
	23	20	9	
	24	20	5	
	25	21	7	
	26	16	9	40
	27	16	12	
	28	18	12	2
	29	23	9	
	30	26	10	5
	31	21	12	

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Table 15. September 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date	High (°C)	Low (°C)	Precipitation (mm)
September 1	21	6	4
2	19	8	
3	22	6	
4	25	5	
5	28	7	
6	28	10	
7	29	15	2
8	23	16	5
9	25	13	
10	27	11	34
11	26	13	
12	23	14	9
13	21	12	T
14	22	6	11
15	23	7	2
16	23	12	3
17	24	16	2
18	17	15	
19	21	13	
20	17	9	3
21	17	9	8
22	18	5	T
23	20	7	
24	19	9	
25	17	2	
26	23	3	
27	27	8	
28	26	10	15
29	20	11	4
30	16	8	3

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Table 16. October 1987 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
October	1	16	0	3
	2	15	1	3
	3	11	2	2
	4	7	-1	
	5	16	1	
	6	18	8	
	7	12	2	T
	8	7	1	1
	9	9	1	
	10	10	3	
	11	8	1	1
	12	8	-2	
	13	11	-3	
	14	15	-2	
	15	17	2	
	16	22	2	
	17	21	2	2
	18	11	6	1
	19	17	3	
	20	10	4	13
	21	5	0	3
	22	5	0	4
	23	6	1	3
	24	10	-1	2
	25	5	-2	6
	26	10	-3	
	27	12	0	9
	28	10	-1	1
	29	9	-1	1
	30	9	1	
	31	16	1	

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Table 17. May 1988 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
May	1	21	4	
	2	22	2	
	3	17	3	
	4	18	2	
	5	22	5	
	6	24	5	
	7	25	5	
	8	28	10	1
	9	22	13	5
	10	16	12	
	11	20	3	T
	12	24	6	T
	13	18	12	
	14	22	3	
	15	28	7	7
	16	13	12	1
	17	18	7	
	18	23	6	
	19	21	9	
	20	22	11	
	21	26	12	
	22	30	12	
	23	23	16	1
	24	21	12	
	25	19	2	
	26	24	3	
	27	27	9	
	28	30	13	
	29	32	10	
	30	32	14	
	31	33	13	

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Table 18. June 1988 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
June	1	33	13	2
	2	20	10	1
	3	20	7	
	4	24	3	
	5	31	6	
	6	33	10	
	7	32	17	
	8	20	11	1
	9	20	8	
	10	22	2	
	11	27	5	
	12	30	11	
	13	33	13	
	14	33	18	
	15	32	18	
	16	26	13	
	17	27	8	
	18	31	12	
	19	32	15	
	20	33	22	
	21	36	13	
	22	34	20	
	23	26	13	
	24	30	12	
	25	36	16	
	26	25	12	
	27	26	7	
	28	18	12	1
	29	23	8	
	30	22	8	

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Table 19. July 1988 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
July	1	25	5	
	2	27	7	
	3	30	8	
	4	35	10	
	5	37	13	
	6	38	16	
	7	38	18	
	8	36	20	
	9	35	19	1
	10	29	18	1
	11	31	18	
	12	29	14	
	13	33	12	
	14	35	21	
	15	35	14	1
	16	36	27	40
	17	31	20	
	18	31	18	6
	19	28	18	
	20	26	17	
	21	27	15	
	22	27	15	
	23	28	15	
	24	29	12	8
	25	27	17	
	26	27	13	
	27	30	11	
	28	34	17	
	29	33	19	7
	30	30	23	
	31	29	18	

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Table 20. August 1988 temperature and precipitation data for the Horticulture Research Center, East Lansing, Mich.

Date		High (°C)	Low (°C)	Precipitation (mm)
August	1	38	23	
	2	36	24	
	3	36	22	
	4	36	22	
	5	32	22	18
	6	31	19	
	7	32	16	
	8	33	16	
	9	30	18	2
	10	31	21	
	11	32	20	
	12	35	21	3
	13	33	21	
	14	34	24	7
	15	34	20	
	16	31	16	
	17	35	18	34
	18	21	18	4
	19	24	13	
	20	24	13	
	21	25	12	
	22	25	9	14
	23	22	9	2
	24	24	9	
	25	24	13	
	26	23	11	
	27	22	15	5
JP	28	22	14	
	29	21	7	
	30	22	7	1
	31	26	9	