PRODUCTIVITY OF VEGETABLE CROPS GROWN UNDER

SHADE IN HAWAII

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ABSTRACT

'Waimanalo Long' eggplant (<u>Solanum melongena</u> L.),
'Kahala' soybean (<u>Glycine max</u> (L.) Merrill), 'Jumbo
Virginia' peanut (<u>Arachis hypogea</u> L.), 'Waimanalo Red'
sweet potato (<u>Ipomea batatas</u> (L.) Lam.), and 'Green
Mignonette' semihead lettuce (<u>Lactuca sativa</u> L.) were
field-grown in two seasons at Waimanalo, Oahu, Hawaii with
five artificially produced levels of shade (0, 30, 47, 63,
and 73%). Yields and vegetative growth of eggplant,
soybean, peanut, and sweet potato were linearly decreased
with increasing shade levels. Compared to unshaded
controls, yields of semihead lettuce increased
significantly from 8100 kg·ha^{-1} to 13,600 kg·ha^{-1} by
30% shade in Fall 1986. During Spring 1987, semihead
lettuce yields were reduced only slightly from unshaded
levels of 22,000 kg·ha^{-1} by increasing shade up to 47%.
Eggplant, soybean and lettuce maintained index leaf areas
similar to unshaded controls as shade intensity increased,
at the expense of leaf dry weight. By comparison, both
leaf area and leaf dry weight of peanut index leaves
decreased as shade increased. Leaf area and leaf dry
weight of sweet potato did not respond to shading.

To further investigate the effects of shade on leafy vegetables, 'Green Mignonette', 'Salinas', 'Parris Island Cos', and 'Amaral 400' lettuce (<u>Lactuca sativa</u> L.), 'WR-55 Days' Chinese cabbage (<u>Brassica rapa</u> L. Pekinensis Group), 'Waianae Strain' green mustard cabbage (<u>Brassica juncea</u> (L.) Czerniak), 'Tastie Hybrid' head cabbage (<u>Brassica oleracea</u> L. Capitata Group), and an unnamed local selection of bunching onions (<u>Allium cepa</u> L. Aggregatum Group) were field-grown in two seasons at the same location with the same five artificially produced levels of shade. Yields of cos lettuce, green mustard cabbage, and bunching onions were irresponsive or negatively affected by shade in both seasons. Yield responses of the other crops to shade varied seasonally. Optimum shading of 30 to 47% increased 'Green Mignonette', 'Salinas', and 'Amaral 400' lettuce by 36% and head cabbage and Chinese cabbage yields by 23% and 21%, respectively, compared to full-sun plots in some trials. Index leaf areas similar to unshaded controls were maintained as shade intensity increased, at the expense of leaf dry weight in all crops except 'Salinas' and 'Parris Island Cos' lettuce. Maximum rates of net photosynthesis (Pn) were attained at about two-thirds of full sunlight (1500 $\mu mol \cdot s^{-1} \cdot m^{-2}$).

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CHAPTER I

INTRODUCTION

The ever-increasing demand for food worldwide has
brought a new urgency to the search for improved management
and cultural techniques of crops and improved agricultural
land utilization, among many other factors. The decreasing
availability of good agricultural land and the high costs
of land and agricultural inputs are becoming serious
limiting factors to increased agricultural production in a
number of areas, especially in the tropics (ICRISAT, 1981;
Stelly, 1983). These problems necessitate the development
of agricultural systems which make intensive use of the
land, as well as using more efficient and cost-saving
farming methods, without adversely affecting quality or
yield. One such intensive land-use method with a potential
for increasing food production is the practice of mixed
(multiple) cropping (Ezumah et al., 1982; Huxley, 1983;
Ofori and Stern, 1987). This is the practice of growing
several crops on the same piece of land, either in
succession or simultaneously. The system is widely
practiced, especially in developing countries, in order to
provide a buffer against the loss of a single crop due to
adverse natural conditions or a fall in market prices of a
certain crop (Beets, 1982; Gomez and Gomez, 1983).

Environmental factors or agricultural inputs are also
better utilized by multiple cropping, for different crops
have different nutrient, sunlight, water, and space
requirements. This efficient input utilization is of
importance to all farmers, but especially to those with
little or no capital available to pay for inputs such as
water, pesticides, and fertilizers. By producing several
types of crops on a single piece of land, farmers also have
available to them a wide range of food, fodder, fiber,
and/or timber crops for personal consumption (Widagda et
al., 1984).

A multiple cropping system is a complex system,
however, which requires knowledge of several types of crops
and their interactions. When several crops are grown
simultaneously on a single piece of land, between-crop
interactions must be considered. One such interaction
which can have substantial effects on productivity is that
of shading by an associated crop, a problem which occurs
when crops of different heights are grown together (Nair,
1977; Nair, 1983). The fact that about ninety percent of
the dry weight increase of plants arises directly from
photosynthesis (Osman and Milthorpe, 1971) indicates that
the availability of sunlight can be the most significant
determinant of plant productivity. Therefore, it can be
argued that a primary means whereby the greatest crop

productivity can be attained is to keep the photosynthetic system operating at its optimum capability (Loomis and Williams, 1963; Loomis and Gerakis, 1975). It may be assumed that this indicates providing the crop with the greatest amount of radiant energy available. However, studies carried out on a wide range of plants on the effects of reduced photosynthetic photon flux (PPF) have shown that great variability of response exists between and within crop species. Most plants respond to variations in available radiation by some type of morphological and physiological changes. Specific responses, however, depend on a number of factors, including species and cultivar, the light conditions under which a crop was grown, the light saturation point of the leaf canopy, and other environmental factors, especially temperature (Hesketh and Moss, 1963; Sales, 1975; Knight and Mitchell, 1983; Ketring, 1984; Martin, 1985).

Under temperate climatic conditions a decrease in amount of radiant energy received most often results in a decrease in plant productivity, due to a reduced photosynthetic rate (Bierhuizen et al., 1973; Whiteside et al., 1975; Gray and Morris, 1978). However, this is often not the case in tropical and subtropical environments. Shading of plants in these areas in many instances produces no adverse results on productivity, especially yield. A reduction in the amount of available photosynthetic photon

flux (from about fifteen to fifty percent full sunlight) has been found to produce equivalent or even improved yields compared to crops grown under full sunlight conditions (Mattei et al., 1973; Eriksen and Whitney, 1984; Smith et al. 1984). A number of factors have been suggested for this neutral or beneficial effect on crop yields of reducing incident radiant energy. Under bright, cloudless sky conditions, maximum irradiance in tropical and subtropical areas is high: Jong et al. (1982) and Glenn (1984) reported daily radiation totals of 43 $mol \cdot m^{-2}$ in Hawaii and Arizona, respectively. Solar inputs of 2040 $\mu mol \cdot s^{-1} \cdot m^{-2}$ have been reported in southern Australia and South Africa (Sales, 1975; Smith et al., 1984). This is in comparison to radiation levels of 4.3 to 26 $mol \cdot m^{-2} \cdot day^{-1}$ recorded during the growing season in middle latitude regions (Glenn, 1984).

Many plants light saturate at solar radiation levels well below those found in tropical and subtropical areas (Bowes et al., 1972; Sale, 1974; Glenn et al., 1984). Some shading (to the light saturation point of the crop) would, therefore, not limit photosynthetic rates to the detriment of plant productivity. On the contrary, shading may actually be beneficial for increased plant productivity, by mitigating other environmental stresses such as high temperatures and low vapor pressure densities (Morris et

al., 1957; Doorenbos and Pruitt, 1977). Stunted, deformed plants (e.g. elongated bulbs, twisted leaves, tipburn) and lowered yields have been reported to occur when unadapted plants are grown in hot, high sunlight conditions (Tibbitts and Rao, 1969; Leopold and Kriedemann, 1975; Yamaguchi et al., 1975; Nothmann, 1977a; Wurr et al., 1981; Sajjapongse and Roan, 1983; Ketring, 1984). This indicates that shading, either by means of a multiple cropping situation or through artificial shade, to the light saturation point of the particular crop, could be an important management technique in both developing and developed areas.

The Objectives

Carry out studies on twelve vegetable crops ('Waimanalo Long' eggplant, 'Kahala' soybean, 'Jumbo Virginia' peanut, 'Waimanalo Red' sweet potato, 'Green Mignonette' lettuce, 'Salinas' lettuce, 'Parris Island Cos' lettuce, 'Amaral 400' lettuce, 'WR-55 Days' Chinese cabbage, 'Waianae Strain' green mustard cabbage, 'Tastie Hybrid' head cabbage, and an unnamed local selection of bunching onions) in order to:

1) determine characteristics of leaf morphology as influenced by shading.

2) observe differences in stages of development and physiological maturity between shade treatments.

3) determine photosynthetic rates over a continual range of photosynthetic photon flux up to full sunlight.

4) evaluate yield parameters resulting from decreasing amounts of total photosynthetically active radiation received.

CHAPTER II

REVIEW OF LITERATURE

Multiple cropping is an ancient practice of growing several crops on the same piece of land. This concept includes relay cropping or growing crops in succession, intercropping, the growing of several types of annuals in close association with one another, agroforestry, where annuals are planted under forest trees, and multistoried cropping, where different statured crops (usually horticultural) are planted together (ICRISAT, 1981; Huxley, 1983; Ofori and Stern, 1987). Traditional farmers, especially in the tropics, often prefer to grow a range of crops, rather than concentrate on a monoculture, in order to minimize risks of disease or pests ruining a crop or a drop in market prices of a certain crop. Multiple cropping also helps in providing a variety of foods for the farmer's subsistence needs (Ezumah et al., 1982; Andrews and Kassam, 1983). This means greater yield stability in a variable environment, with a regularity in food supply (Beets, 1982). Better utilization of environmental factors may be obtained, especially solar radiation, soil water, nutrients, and space (Norman, 1979). Higher yield and greater gross return per unit area is obtained, as well, the principal extra input needed being labor. Labor in tropical countries is generally in excess and its cost as

an input is low, while other inputs such as fertilizer or
pesticides may be too costly for farmers to use (Ahmed and
Rao, 1982). Protection against soil erosion, weeds, and
water loss are additional factors favoring the use of
multiple cropping systems.

Multistoried cropping

Multistoried cropping is practiced in many regions of
the world for a number of reasons. In Java, for example,
traditional multistoried cropping systems have fulfilled
the needs of smallholders for centuries by combining
agricultural crops with horticultural tree crops (Widagda
et al., 1984.). Socioeconomic advantages of such a system
are that the perennials have a long lifespan and their
products are usually readily salable, thus the development
of an area with perennials represents an accumulation of
income-producing capital--a form of semipermanent
investment or security. When the perennial is a cash crop,
the combination of an annual crop subsistence base and a
permanent cash income producer provides economic stability
and the potential for an improved living standard (Norman,
1979). Perennial trees are more able to survive stresses
of wet or dry years with a minimal effect on their
subsequent productivity compared to annuals (Nair, 1977).
Often the management techniques for tree crops are less

arduous and expensive than those required for annual crops; for example, perennial crops usually require less seasonal labor input, making them easily integratable with an annual cropping system.

With the long lifecycle of perennial crops, the soil is almost always under vegetation, thus erosion is reduced and soil conservation enhanced. Shading of the soil is more complete with an annual-perennial intercrop system, which can reduce evaporative water losses from the soil surface. The root systems of annuals and perennials dominate different soil depths, allowing for more efficient subsoil water and nutrient use. For example, the root system of a coconut palm is shallow and not wide-spreading, therefore, it does not interfere much with the root systems of intercrops (Nair, 1983). Air temperatures in a mixed crop are cooler because the system is more closed and less ventilated.

The care given to the annuals also benefits the perennials, which are often neglected when grown as a monocrop. Cultivation between the trees, a necessary part of annual plant production, often is not carried out when the trees are in pure stands. Fertilization of the annuals also benefits the perennials. Intercropping under coconuts has usually resulted in an increase rather than a decrease in nut yield because of the care given to the intercropped annuals (Nair, 1977).

Many tree crops, such as coconut, rubber, and oil palms, are often planted with rather wide spacings, thus occupying relatively small portions of the ground and letting through most of the incident solar radiation. This has permitted the successful interplanting of peanuts, sweet potatoes, maize, upland rice, soybeans, and cassava in many plantation crops (Beets, 1982).

Interplanting with crops is often feasible with other tree plantings, as well, especially when the trees are young. At this time fast-maturing annuals could be grown as intercrops, quickly covering the ground between the trees for soil erosion prevention and weed control. These annuals can also provide income to the farm household during the unproductive stage of the slow-maturing perennials (Gomez and Gomez, 1983). For example, in Puerto Rico tropical forests were thinned in preparation for planting shade-grown coffee, cacao, or tea crops. Vincente-Chandler et al. (1966) advocated the planting of shade tolerant fast-maturing crops in the interspaces before the main crop came into production. They also advocated the planting of shade tolerant crops in the thousands of acres of abandoned hillside coffee plantations to provide economic productivity and to protect against soil erosion.

For multistoried cropping, crops of different stature and rooting habits are grouped together to form compatible combinations so as to enable interception and utilization of light at different vertical intervals (Nelliat et al., 1974). The greater the competition gap between species to be intercropped, the closer the yields will be to sole crop yields, because different environmental factors will be exploited by the different species (Devos and Wilson, 1979).

In order for a multistoried cropping system to be successful, several criteria have to be met (Nair, 1979, 1983). The leaf canopies of the various crops must be in several different vertical layers with the tallest component having foliage tolerant of strong light and high evaporative demand. The understory plants should require or tolerate shade and/or high humidity. The understory should not grow as tall as the main crop, exploit the same root zone, or have an economic life longer than the main crop. It should not be more susceptible than the main crop to diseases they have in common or demand management techniques which could damage the main crop or its environment. The intercrop should not act as a parasite on the main crop, otherwise the yields of both will be affected. The soil and other environmental factors must be suitable for both crops. The yields of species in intercropping systems normally are less than their yields

when grown in pure stands, therefore, a multistoried system is only beneficial if the combined yield of both crops is greater in monetary returns than that of the main crop itself (Nair, 1979, 1983). Because the perennials are committed to the land for decades, the strategy to use for intensive multiple cropping is to have parallel combinations of crops in such a way that the planting pattern of the main crop need not be altered to suit the needs of the secondary crops.

Intercropping

Much information, based both on traditional farming experience as well as scientific research, exists on the types of crops which have been successfully grown as intercrops under trees in tropical and subtropical environments. Where the intercrop and main tree crop are properly fertilized and managed, a large number of additional crops can be successfully grown with the perennial crop. Most annual grain crops such as corn and sorghum often suffer substantial yield reductions when grown under shade, although they are often successfully used as intercrops (Kass, 1982). Crops that have performed well under coconut canopies include taro, arrowroot, yams, cassava, pulses, several kinds of vegetables, sunflowers,

soybeans, and sweet potatoes depending on tree spacing and environmental conditions (Leela and Bhaskaran, 1978; Varghese et al., 1978; Moreno, 1980; Gomez and Gomez, 1983; Nair, 1983). Perennial intercrops which are generally grown during the reproductive stage of coconuts and tolerate shade well include bananas, pineapples, coffee, cacao, rhizome spices, cinnamon, nutmeg, cloves, and black pepper (Nair, 1979; Gomez and Gomez, 1983).

A number of studies have been undertaken which deal with intercropping of a variety of crops under a main crop of bananas or plantains (Karikari, 1972). Devos and Wilson (1979) discussed an economic survey carried out in Nigeria which demonstrated that intercropping in plantain plantations caused only a slight decline in plantain fruit yields compared to sole cropped fields. Maize, cocoyams, cassava, vegetables, rice, beans, yams, and sugarcane have all been used for this purpose. Maize and cassava performance was poor in intercropping trials with plantains, while cocoyams (Xanthosoma sigittifolium) gave the best results in terms of labor input required and the cost of production.

Intercropping of banana with cowpeas, maize, and sweet potato was studied in the windward Caribbean islands, where small farmers commonly interplant banana with permanent fruit trees and vegetables (Rao and Edmunds, 1984). Cowpea and sweet potato yields were not affected by intercropping,

but maize yields were reduced. Banana bunch weight was not affected, although there was an increase in the number of days to shooting and harvest.

In Puerto Rico, the effects of shade trees on the yields of cocoyams, maize, plantains, tobacco, and bananas were examined (Vicente-Chandler et al., 1966). The shade trees used were _Inga inga_, which were pruned to produce 50% shade. Maize and cocoyams yields were severely reduced under shade as compared to full-sun treatments, while plantain yields were only slightly decreased and cured tobacco yields were similar in full sunlight and under shade. Shaded banana trials resulted in two times the marketable yields as those obtained under full-sun. This was attributed to reduced damage caused by leaf spot disease. The shaded bananas matured somewhat later and at a more uniform rate compared to the controls.

In Southeast Asia, rubber plantations are often interplanted successfully with fruit trees, pepper, coconuts, and a variety of vegetables, while in Africa multistoried cropping is also an old concept. Here timber trees are grown as shade trees over coffee and bananas intermixed with a wide range of annual food crops such as maize, beans, melons, and cassava (Keswani and Ndunguru, 1982). Cacao and food crops such as cassava, cucumbers, and sweet potatoes, are often grown together, especially in

the first few years after the cacao is planted. Cacao itself is often grown under shaded conditions, as are coffee and tea (Murray and Nichols, 1966; Hadfield, 1974).

Simple mixed annual and perennial subsistence farming systems in the Pacific islands have been in existence for hundreds of years. Tuber interplanting with tree crops (primarily breadfruit and coconut) was practiced in Oceania before the spread of rice and other seed crops from Asia (Norman, 1979). Rachie (1983) is of the opinion that breadfruit (Artocarpus spp.) has considerable potential for use in intercropping systems because it is high yielding and nutritious and, together with annual staple crops, can provide a balanced diet.

In temperate multistoried cropping situations, strawberries have often been used as an intercrop in newly established orchards. Light was considered to be the primary limiting factor in the successful production of strawberries after the first three years of growth of a closely spaced bush apple orchard (Jackson, 1983). Under wider spacing, the strawberries could be grown for nine years. Strawberries require high light intensities for optimal growth, but do show some adaptation to shaded environments. Strawberries planted between grapevines of varying ages, had similar flowering dates and yields although the light intensity varied from 42 to 20 klux (Jackson, 1983).

Adaptive changes to shading and shade tolerance

In the natural environment, plants commonly are
subjected to shaded conditions. Plant species which have
evolved under continual conditions of shade have developed
special photosynthetic and morphological features, and are
called "shade plants". The leaves of many forest and
native species which grow in shaded habitats "light
saturate" (achieve maximum photosynthetic rates which do
not increase when light levels are increased further) at
low levels of solar radiation, and understory leaves may
even die if exposed to full solar radiation (Allen et al.,
1983). Those plants commonly growing in a sunny
environment are known as "sun plants". On a smaller scale,
leaves on an individual plant can be either "shade" or
"sun" leaves, depending on the microenvironment surrounding
them.

Plants which occupy shaded habitats are incapable of
high photosynthetic rates, but perform efficiently at low
light intensities (Bjorkman and Holmgren, 1966). Near the
light compensation point, their photosynthetic rates will
be higher than sun loving plants, but at high light levels
this advantage is lost due to the limited ability of their
CO_2-fixing apparatus. However, some species grown under
shade can "adjust", i.e. use irradiation at levels higher
than that under which they were grown. Thus they can

fully utilize the high irradiation levels present in
sunflecks (Friend, 1984).

On the other hand, those plants which grow under high
light intensities have a high capacity for photosynthesis
at saturating levels of light, but photosynthesize less
efficiently under low light intensities. The sun leaves of
Ficus benjamina displayed a diurnal trend in net
photosynthesis, with maximum rates occurring in the morning
hours. The net photosynthetic rates of shade leaves,
however, did not decline until mid-afternoon. Also, shade
grown leaves had a photosynthetic advantage over sun grown
leaves at low light levels, while sun leaves had the
advantage at higher light levels (Fails et al., 1982).

These characteristics are not limited to species
which have evolved in a certain habitat, but can be induced
by the light intensity under which a plant is grown. Light
and shade adaptation have been observed in plant species
ranging from forest trees to marine phytoplankton (Loach,
1967; Falkowski and Owens, 1980). For example, when a few
leaves of a sun species are placed under low light
intensities, they will display light saturation curves
similar to those of shade plants. Such differences between
shaded and unshaded leaves on single soybean plants were
observed by Beuerlein and Pendleton (1971). Leaves lower
on the plant had lower photosynthetic rates compared to

those near the top of the canopy, not due to age, but rather to acclimation to lower light levels. On the whole, however, the adaptability of a plant to a certain light environment is inherited; it is determined by the genotype and results from genetic adaptation to a certain light environment (Boardman, 1977).

Sun and shade plants (and leaves) can be distinguished by certain morphological differences. Shade species have characteristic alterations which enhance their ability to intercept light energy. Jackson (1967) studied the sun and shade leaves of 21 deciduous tree species and found that shade tolerant species have thinner sun leaves and less reduction in thickness in the shade than did shade intolerant species. The shade leaves were thinner, with a larger volume of air space, thinner palisade tissue, and fewer stomata. An increased foliar surface under shaded conditions has been observed in a large number of plant species, ranging from Citrus to mungbean (Leopold and Kriedemann, 1975). The sun leaves of apple trees have a greater specific leaf weight and a lower transmittance than shade leaves. The reflectance of both leaf types is similar (Palmer, 1977). Leaf area, therefore, is not a good indicator of photosynthetic rates in many plants. Bhagsari and Brown (1986) found negative correlations between CO_2 exchange rate and leaf area in a wide range of plants, including peanut, soybean, and sweet potato.

When sun species are placed under conditions of shade, besides the foliar change, stem elongation occurs, resulting in higher stem weight ratio and lower leaf weight and leaf area ratios (Corre, 1983a). When the photosynthetic rate is limiting, a greater part of the photosynthate goes to the stems rather than to the roots (Martin, 1985). Shade reduces the production of dry matter, primarily in storage organs. For example, the sucrose concentration in sugar beets increases with increasing light intensity (Ulrich, 1952).

In shade plants, besides the reduction of mesophyll size and the enlargement of laminar surface, chloroplasts also become rearranged in photosynthetic tissues and light harvesting apparatus are modified. The photosynthetic apparatus tends to adjust to a specific light environment in order that the available light energy is utilized most efficiently (Bjorkman and Holmgren, 1963). A higher proportion of chlorophyll b has been found in the leaves of understory rainforest species, which enhances the light absorbing capability in the wavelength region between the red and blue bands of chlorophyll a. This allows greater absorption of the light which passes through a leaf canopy (Boardman, 1977). Similar morphological adaptations were observed in Atriplex patula, a sun plant, when grown under three different light intensities (Bjorkman et al., 1972).

Other physiological bases for shade tolerance include the lowering of respiration and transpiration rates, leading to slower metabolic rates (Grime, 1965, 1966; Fails et al., 1982). Thus net photosynthesis (gross photosynthesis minus respiration) of shade plants may depend on both conservation of energy and efficiency of its capture.

Comparisons between the shade tolerant Impatiens hybrida and sun tolerant Pelargonium x hortorum revealed that the Impatiens had decreased diffusive resistance, increased chlorophyll content and smaller, denser stomatal areas in leaves held under low quantum flux density compared to the sun tolerant plant (Armitage and Vines, 1982a). High quantum flux density does not result in high photosynthetic rates in Impatiens due to either an inhibition of chlorophyll synthesis or accelerated degradation of the pigment (Armitage and Vines, 1982b). Clough et al., (1980, 1983), however, studied genotypes of Solanum dulcamara from sun and shade habitats and found no consistent differences in photosynthesis or total plant dry weight. They concluded that previously reported differences may have been the result of the persistent after-effects to changes in leaf water potential and not an adaptive response to growth light level.

The light compensation point of a leaf, the point where CO_2 uptake is balanced by CO_2 production, is based

primarily on its dark respiration rate (Bohning, 1949; Bohning and Burnside, 1956; Gaastra, 1962). Wilson and Cooper (1969) found that the light saturation level was not a fixed value in Lolium perenne but that it increased with increasing CO_2 concentration.

In coffee plants maximum apparent photosynthesis occurred at 6000 f.c. Above this light intensity photosynthetic rates decline, apparently due to an impairment of the photosynthetic mechanism by too high intensities (Tio, 1962). Kok (1956) also found that high light intensities impaired the growth and photosynthesis of green algae. Again the cause was the destruction of the photosynthetic pigment complex and secondary photo-oxidation reactions. In pasture grasses and other plants the rate of photosynthesis at low light intensities increases rapidly as light intensity increases, but at higher intensities the rate of increase falls off and light saturation will be reached with no further increase in photosynthetic rate (Gaastra, 1962; Cooper and Tainton, 1968).

Leaf movement and leaf orientation of plants in shaded habitats maximize the capture of the available radiant energy. Leaves and leaflets of many Leguminoseae are heliotropic, which place them perpendicularly to incident light at low radiation levels. The positioning of leaves in

a canopy is carried out in such a way that leaf mosaics are formed, meaning light interception is maximized and mutual shading is minimized (Grime, 1965, 1966; Leopold and Kriedemann, 1975).

Light penetration through trees

Probably the major area of concern in agroforesty is that of light penetration through the canopy of the tree crop in sufficient amounts to support the growth of the intercrop. Where the understory crop is grown only in the first few years after planting the trees, there is little interference in light interception. As the tree canopy expands over time, light interception becomes a greater concern. The shade provided by their canopy becomes permanent in the landscape and must be treated as a factor beyond the farmers' control. This problem led Tieszen (1983) to propose that for intercropping, ideally, the canopy should consist of a C_4 overstory and C_3 understory, because the light saturated rates of C_4 plants are usually greater than those of C_3 plants. Thus, in closed canopies, the greater quantum efficiency of C_3 could become important. Crops with the lowest light saturation levels would appear to be most suited to the understory, with them being able to perform as well under a degree of moderate shade from a tree crop as they could in the open. Single

leaves of C_4 crops such as maize, do not become light saturated in full sunlight, while sugar beet and soybean leaves (C_3 plants) have been found to saturate at about half of full sunlight. With leafy crops, such shading could even be beneficial, redirecting a larger fraction of assimilates towards economic yield (leaf as opposed to total net production) (Jackson, 1983).

The amount of light energy available to plants in natural situations varies with the amount of light energy reaching the surface of the earth. This is dependent on latitude, time of year, and atmospheric conditions, the presence of taller plants and within crop shading (Black, 1957). The light penetration into an orchard depends on overall leaf area index, the combination of solar angle and altitude, angle of row with respect to solar azimuth, angles, size, and shape of leaves, leaf transmissibility and reflectance, spacing, and orientation of the trees (Baker and Meyer, 1966; Pearce et al., 1967). The open space commonly left around fruit trees leads to much of the lower part of the tree structure being more accessible to light from near the horizon than from vertically above (Jackson, 1970).

Light intensity in fruit tree orchards has been studied for both temperate and tropical trees. Several researchers have carried out a number of studies to

characterize the light microclimate in apple trees. Doud and Ferree (1980) found that diffuse light in the mid- and lower canopy of an apple tree was much less than expected, with a shift from predominantly sunlit to predominantly shaded conditions occurring with depth into the canopy. Palmer (1977) studied light transmittance by apple leaves and canopies and observed that mean light absorbance over the 400 to 700 nm range was about 85%. Palmer and Jackson (1977) studied the light interception pattern of various apple orchard planting systems and found that fruit orchards, particularly those grown in modern hedgerow systems, allow more light to penetrate to the ground compared with other crops (Jackson and Palmer, 1972; Palmer and Jackson, 1977).

Most of the studies dealing with light penetration through tropical fruit tree plantings have focused on the coconut palm. The intensity of light falling on the ground at different times of day in a coconut-cacao crop mix was measured during different seasons of the year in western India (Nair and Balakrishnan, 1976). The further away from the coconut trunk the light incidence was measured, the more light penetration which occurred. Considering the plantation as a single unit for these light studies, it was observed that during the peak bright hours of the day, an average of 44% light was intercepted by coconuts in a pure palm stand. A sudden increase in intensity was observed in

the early morning hours, with a steep decline occurring in the late afternoon, independent of season. Gomez and Gomez (1983) report a figure of 88 to 43% of normal sunlight striking the ground through a coconut canopy, penetration being dependent on tree spacing.

The orientation of the long palm leaves of a coconut permits part of the solar radiation incident on the foliage to pass through to the lower profiles and the ground. High reflectance of thick-cuticled coconut leaves and the position of the leaflets cause scattering of incident radiation in all directions. As a result, the light intensity at the plantation floor even directly under the canopy shade of the tree can be higher than expected.

The magnitude of this radiation penetration, along with the amount of shade cast by the coconut canopy vary depending upon the age of the palms. Starting with age 8 to 10 years, up to age 25, only about 20% of the incident sunlight is transmitted. After 25 years the percent light transmission progressively increases and canopy coverage of the ground decreases. After attaining maturity there is little change in the spread of the coconut crown but a continued increase in height. At 40 years the light transmission is about 50% due to this increase in height (Nelliat et al., 1974; Nair, 1979).

Gomez and Gomez (1983) and Nair (1977) divided the lifecycle of evergreen tropical tree crops into three stages: the preflowering stage, the reproductive stage, and the stage of senescence. Light interception by the perennial canopy is maximum during its reproductive stage, with the minimum interception occurring during the early preflowering stage. During the preflowering stage, the perennial canopy is not yet fully developed, and therefore intercepts only a small fraction of the available solar energy. At this stage enough sunlight penetrates to the ground to support a large variety of intercrops. At the reproductive stage, the perennial crop reaches its full size, allowing very little light to penetrate to the ground, and there is maximum shading between trees. If crops are interplanted during this stage, they must have good shade tolerance. The growing of annual grain crops and vegetables is not commonly practiced during this stage because of the lack of fast-maturing annuals that can tolerate low levels of sunshine. Shorter statured perennials are often planted at this time, then continued on through the senescence stage (old age) of the main perennial crop. Annuals may once again be planted during the stage of tree senecence, or young trees may be established which will eventually replace the main crop.

Shading by tree canopies decreases light intensity and also affects spectral quality. The spectral composition of

light is changed in a leaf canopy mainly as a consequence
of the light being absorbed by chlorophyll. The proportion
of visible to near infrared radiation decreases beneath
hedgerow orchards and within the patches of shade the
proportion of blue light increases while red light
decreases (Palmer, 1977). Corre (1983a) found that shade
light is relatively poor in blue and red light, but
relatively rich in green and especially rich in far-red
light. This affects the red to far-red ratio of light
reaching down through the canopy, which can lead to growth
and morphogenic changes in plants in lower parts of the
canopy. These facts were confirmed by Kasperbauer (1971)
through his work with light penetration through tobacco
leaf canopies. Shading in peach hedgerow canopies likewise
resulted in a decrease of the visible to the infrared ratio
(Kappel et al., 1983). This relative enrichment of
730/660 nm radiation in the lower canopy is greater near
sunset than at midday. This type of effect may be greater
for intercropping systems oriented in north-south rows as
compared to an east-west orientation. Near sunset, less
radiation is received by the shorter plants intercropped
between trees with a north-south orientation (Allen, 1974;
Allen et al., 1983; Jackson, 1983). Sinclair and Lemon
(1973) characterized the radiation quality in corn canopies
and found that the radiation incident to the crop remained

spectrally stable throughout the day, regardless of sky conditions. When the sun reached low elevations, a relative increase in 730 nm radiation was observed. Within the canopy the red wavelength was absorbed, while the far-red was highly scattered. This resulted in an enrichment in 730 nm radiation with increasing depth.

Light penetration to a forest floor follows a similar pattern as through a crop canopy. About 60% of photosynthetically useful radiation which penetrates the rainforest canopy is supplied by the numerous small openings in the leaf canopy, causing sunflecks (Evans, 1956; Boardman, 1977). The microclimate under Albizzia trees was studied in India, with findings indicating that 50% of the infrared light was absorbed, compared to the 98% of the visible light which was absorbed. Dappled shade helped to compensate for the poor quality light passing through the canopy (Willey, 1975).

Bjorkman and Holmgren (1963) studied two shade species, Alocassia macrorrhiza and Cordyline rubra, growing on the subtropical rainforest floor. The energy flux reaching the floor was 2 to 3% of the flux above the canopy, depending on the cloud cover. The diffuse light on the floor showed a high proportion of far-red and near infrared light and an increase in the proportion of green light.

Under natural conditions, part or all of a crop canopy is subjected to rapid changes in light intensity for much

of the day. Wind flutter of leaves causing sunflecks, changes in solar position, and swiftly moving cloud formations are the major causes of these light fluctuations. As the position of the sun changes or as clouds move, the irradiance of exposed leaves changes slowly. Light flecks which penetrate the canopy and irradiate the lower leaves move more quickly, while leaf movements may induce both slow light fluctuations due to phototropic movements of leaves and rapid fluctuations due to wind. This non-uniform attenuation of solar radiation results in irregular patterns of high radiation load within the canopy. Net radiation in sunflecks can exceed that above the canopy, while negative values of net radiation can exist in shadows. Sunflecks can be the primary source of the total light reaching lower levels in leaf canopies, especially at midday in tropical regions and can offset the effects of far-red light enrichment in the lower leaf canopy by allowing a greater spectrum of light through the upper canopy.

Studies carried out on these fluctuations revealed that the dry weight increase of all plants examined was not appreciably affected by these variations in light. Plants subjected to slow moving shade accumulated less dry matter than those under fixed or rapid shades (Huxley, 1969). Another study demonstrated that cucumber plants under

fluctuating light were perfect integrators of
photosynthetic rates, not of light (McCree and Loomis,
1969). This means daily totals of radiation received can
be linearly integrated but photosynthetic rates are
nonlinear. The average light transmission factor of a
cucumber canopy can therefore not be used to calculate the
photosynthetic rates of leaves within the canopy. Steady-
state photosynthetic rates may be used to compute rates in
fluctuating light provided that photosynthetic rates and
not irradiances are integrated. Kriedemann et al. (1972)
studied the movement of sunflecks in a vineyard and found
that the intermittent or alternating light cycles were used
with maximum effectiveness for photosynthesis compared to
continuous radiation. This was due to the alleviation of
dark reactions as a major limitation to CO_2 fixation. The
respiratory losses of a leaf deep inside the canopy can be
offset by irradiating up to 1% of its area with light
flecks of a saturating density of radiant flux (Allen and
Lemon, 1972). Sunflecks can thus have a very beneficial
effect in providing much needed radiation to lower leaves.

Light intensity and plant productivity

Crop production can be viewed as the process of
conversion of solar energy into chemical energy in the form
of protein, carbohydrate, fat, and so on through the

photosynthetic apparatus (Nelliat et al., 1974; Nair, 1979). Solar radiation provides the energy for the green plant photosynthetic apparatus and provides the primary energy source to drive evapotranspiration and sensible heat exchange. In fact some 90% of the dry weight increase of plants arises directly from photosynthesis (Osman and Milthorpe, 1971). Thus, the availability of sunlight is often the most significant determinant of plant productivity (Loomis and Williams, 1963; Hughes, 1966). Plants under partial shade, as, for instance, those in intercropping systems would not receive full solar incidence. This would affect their energy gain, but also reduce their potential for water stress (Doorenbos and Pruitt, 1977; Allen et al., 1983). Therefore, it can be argued that a major means whereby the greatest crop productivity can be reached is to keep the photosynthetic system operating at its optimum capability. This can be achieved in a number of ways, including the development of cropping systems whereby the total production from a unit area of land is increased through growing crops simultaneously, by improving the efficiency of conversion of light, and by improving the structure of individual plants or plant communities to more efficiently intercept light (Hesketh and Moss, 1963; Loomis and Gerakis, 1975; Reddy and Willey, 1981).

Of course, the diurnal and seasonal course of solar radiation and solar elevation also greatly influence photosynthesis (Gaastra, 1962). In tropical areas near the equator seasonal variation in total daily radiation is small, due to relatively minor changes in sun angle and amount of time of solar incidence. In many areas no distinct periods of clear and overcast days are common, either. In areas where summer rainfall is prominent, the greater daily radiation of the season caused by longer days and higher solar angles is reduced due to greater cloud cover. The seasonal variation in daylength is minor in the tropics compared to temperate regions, but can still be of agricultural importance due to the photosensitivity of tropically adapted plants (Norman, 1979).

Leaf area index (LAI) is the measure of half the leaf surface divided by area of individual plant spacing or arbitrary ground area. To fully utilize incident solar radiation for maximum dry matter production, ground cover should be as dense as possible without causing mutual shading (Blackman and Black, 1959). The rate of dry matter production by a single plant or a crop will increase as the LAI increases up to a certain maximum value. After this point, if the LAI increases further, the rate of dry matter production will decline due to heavy shading of the lowermost leaves (Stern and Donald, 1961; Tanaka and Kawano, 1966). Optimum leaf area index varies with

saturating light intensity, light compensation point, plant type, and light distribution within the plant stand (Pearce et al., 1967). In general, however, it can be stated that the value of the optimum index increases as radiation increases. The optical properties of the leaves themselves also influence the proportion of incident light which is reflected, absorbed, and transmitted (Kriedemann et al., 1964).

During the total growing period of a crop only about 1 to 2% of the incident solar radiation is converted into chemical energy. In annual crops this low efficiency is in part caused by the low LAI in the beginning of the crop cycle. For a closed crop canopy this efficiency can increase to 4 to 9%. Optimum light utilization occurs when the light distribution is as uniform as possible, because then the fraction of leaves exposed to light intensities beyond saturation or below compensation is minimal (Gaastra, 1962). Reduction in net photosynthesis resulting from suboptimal PAR levels within a canopy is probably partially mitigated by the pentration of diffused and intermittent light into leaf canopies.

Shading

The deliberate shading of soil, seedlings, plants, and crops is carried out world-wide and especially by smallholders in developing countries to protect them from environmental stresses. The yield capacity of plants can be improved through shading for a number of reasons. Shading by trees can prevent water stresses through evapotranspiration and nutrient stresses by matching growth to available nutrients, stabilize differences in day and night temperatures, and protect against rain, hail, and wind impact. A decrease in airflow can beneficially influence the transport of water vapor, heat, movement of CO_2 from or to surfaces, and reduce weed growth and sun scorch. If crops are planted under trees, the leaf litter can form a mulch, which decomposes to release plant nutrients, reduce evaporation from the soil, and help to curb soil erosion. Pests and diseases are often discouraged by shade (Morris et al., 1957; Bowman, 1972; Stigter, 1984).

A broader scientific knowledge of the effects of shading can be helpful in developing cropping systems and planting methods which will optimize productivity. Trials which use artificial methods (industrially-produced materials) to reproduce natural shade are commonly used to investigate the effects of shade on plant growth. Fortuin

and Omta (1980) created artificial shade using plant
materials by constructing bamboo frames covered by the
grass Imperata cylindrica. Different shade levels were
made by varying the quantity of grass used. However, these
methods have been criticized for producing information
which is not applicable to natural situations (Young,
1975). Smith and Whiteman (1983) criticized work with
pasture legumes which attempted to evaluate the relative
tolerances of different species by growing them under
artificial shade. They stated that this system neglected
the other competitive effects of the natural environment,
in this case an established tree crop. Jackson (1983) was
also aware of this problem and stated that it is unwise to
assume that simple shading trials with screens will produce
valid information. Artificial screens do not influence the
spectral composition of light in the same way that a
natural shade producer would. The changing light
environment due to the movement of leaves, clouds, or the
seasonal development of a canopy cannot be accurately
represented by artificial shade, either (Barden, 1977). As
an example, soybeans have been characterized as being
nonefficient CO_2 assimilators because they were found to
saturate at low light intensities and had low maximum rates
of photosynthesis.

Huxley (1967), on the other hand, advocates the use of artificial shading, being of the opinion that artificial shading experiments on seedlings or small plants can provide a more critical and more widely applicable analysis of some of the effects of solar radiation on crop growth compared to natural shade experiments.

Shading studies

Numerous studies have been undertaken dealing with the reduced photosynthetic rates and/or reduced plant products obtained when sunlight intensities are not optimal. Early important work on this subject was carried out by White (1937) and Blackman and Wilson (1951) on a number of different plant species. They found that the reductions in net assimilation caused by shading was similar in all species studied. Net assimilation rate during the season of active growth is linearly related to the logarithm of the light intensity, but does not hold when the relative growth rate is small. Similar results were obtained by Hiroi and Monsi (1963) with their work on sunflower. Studies dealing with the problem of shade on crops have ranged from agronomic crops to forest trees to horticultural crops. Studies have even been undertaken with weed species in order to determine new methods of control (Lee and Cavers, 1981). In the majority of cases,

shading (reduction of light from full sunlight intensity) resulted in reduced plant performance, although the amount of shading needed to produce results varied from species to species and even within species. Light intensity also influences the effects of low nutrient availability, with high light intensity and low nutrient supply causing a much greater decrease in relative growth rate (Corre, 1983b).

Radiation can be measured in a number of different ways, including radiometrically, photometrically, and the measurement of photosynthetically active radiation (PAR) (Biggs, 1986). Radiometry deals with the properties of radiant energy and is reported in joules (J) or watts (W). Some radiometric measurements have also been reported in calories (cal). Photometry is the measurement of visible radiation and is reported in lumen (lm), candela (cd), and lux (lx). Photosynthetically active radiation describes the wavelengths within the 400-700 nm waveband and are reported as moles (mol) photons or Einsteins (E). Complications arise when conversions between these units are attempted, because many different factors (e.g. type of measurement, light source, etc.) are involved in arriving at a certain measurement. For this reason, no attempt has been made in standardizing units in this discussion.

Shading studies: Grasses

Most shading studies which have been carried out have
dealt with forages, grasses, and grains. The basic
climatic factor limiting production of pasture grasses is
the input of solar energy (Cooper and Tainton, 1968). Many
tropical grasses are not light saturated under full
sunlight conditions, which contrasts with a light
saturation point for most temperate grasses at 80 to 100%
full sunlight. The rate limiting factor in these regions
generally is not solar incidence, however, but rather water
stress due to high evapotranspiration rates. For pasture
grasses, the quantity of light energy available rather than
its intensity is important, but still different pasture
species have different shade tolerances (Black, 1957).
Smith and Whiteman (1983) evaluated eight tropical grass
species under different coconut densities producing five
different shade levels ranging from 100 to 20%. Several of
the grass species were well-adapted to the shade in coconut
plantations. The productivity and persistence of these
grasses depended on their adaptability to shading and to
competition from the coconut palms.

Dennis and Woledge (1983) found that white clover
grown under low light intensities (30 $J \cdot m^{-2} \cdot s^{-1}$) had
photosynthetic capacities 30% lower than those plants grown
without shade (120 $J \cdot m^{-2} \cdot s^{-1}$). Respiration per unit leaf

area was higher in plants grown in higher light intensities due to lower specific leaf area of these leaves. However, half-expanded leaves moved from shade to sun had photosynthetic capacities as high as those under continuous full-sun. Clover leaves developed in bright light had higher rates of light saturated photosynthesis compared to those which had been shaded. As the clover canopy density increased, however, photosynthesis of the canopy did not decrease as might be expected with increased leaf shading. This may have been due to rapid petiole extension, raising developing laminae to the top of the stand. The differences in photosynthetic rates under different light conditions were due to differences in stomatal and residual diffusion resistances. Leaves grown under dim light adapted to this condition through a higher specific leaf area.

Shading always decreased seed yield in subterranean clover, due to the decrease in the number of influorescences produced per unit area (Collins et al., 1978). White clover plants which were subjected to different levels of constant light increased in weight, even those placed at light levels below their compensation point. This was attributed to plant adaptation of respiration rates to be a constant proportion of their growth rates (McCree and Troughton, 1966). Giving only

60% full sunlight to a pasture sward greatly reduced clover content; however, a further decrease to 40% full-sun had no additional negative effects (Black, 1957).

A reduction of light intensity greater than 74% of full-sun caused a decrease in both top dry matter and root dry matter production, but a reduction of less than 74% had no effect on forage production of tall fescue (Sillar, 1967). An 80% shade for six days increased NO_3-N concentration from 1220 to 4200 ppm in plots receiving 50 kg N/ha (Stritzke and McMurphy, 1982). Another study demonstrated that reasonable fescue turf stands were produced under 70% shade, while intenser shades reduced plant size but not plant density (Wu et al., 1985). Burton et al. (1959) used open mesh cotton cloth to imitate varying degrees of shade that would result as slash pine (Pinus elliottii) trees grew and closed their canopies. This artificial shade was used to study the ability of coastal bermuda grass to adapting to and tolerating different shade levels if planted under the pines. At moderate fertility levels a light reduction of 33% did not greatly affect yield, persistence, or chemical composition of the grass. This means that as long as the trees are small and spaced so that direct light strikes the grass a part of each day, the grass can perform satisfactorily. Lack of light will eventually kill the grass as the trees mature and close their canopies.

Shading reduced the growth rate of dwarf spring wheat, approximately in direct proportion to reduction in radiation due to its effect on net carbon balance of the crop. Small reductions in light intensity, however, had little effect on yield. Shading had the greatest effect 60 to 80 days after seeding, with early and late shading having only minor effects on yield (Fischer, 1975). Solar elevation had an effect on the efficiency with which wheat plants could utilize radiation. As the elevation of the sun increased the contribution to photosynthesis by the lower leaves and leaf sheaths increased (Puckridge, 1972).

Shading of barley plants during different stages of development also influenced grain yield. Shading during ear development caused considerable yield reductions, while no reduction in grain yield occurred from shading during the grain filling period (Willey and Holliday, 1971). Apparently, the competitive ability of barley does not change under differing light intensities. Edwards and Allard (1963) studied the competitive ability of two barley cultivars under different amounts of shade and found that this ability of the two genotypes remained constant over the entire range of treatments.

As is the case with barley and wheat, the sensitivity of rice and maize to shade was greater at certain periods during development, especially during the reproductive period (Earley et al., 1967; Evans and

DeDatta, 1979). Short shading during the vegetative development of maize affected leaf area, plant height, stem thickness, and reproductive development but the final effects on dry matter yield and quality were small. If shading occurred during silking, however, ear size and final ear yield were greatly reduced. Shading also reduced the digestibility of forage maize because the production of total dry matter was more affected than the production of indigestible cell walls. When shading occurred during flowering, reproductive development was greatly reduced, for maize has a short critical period in its development during which adverse environmental conditions cause irreversible damage to reproductive organs (Struik, 1983). In general, however, a significant decrease in measured components in maize (grain stover, total protein, total oil) paralleled a decrease in light availability. Shading of maize leaves located below the ear was carried out in order to detemine the importance of these leaves in grain yield. Restricting light penetration by 75 to 100% significantly reduced grain yields, while reductions of 25 to 50% light incidence on these lower leaves had little effect on per hectare grain yields (Schmidt and Colville, 1967). Different maize hybrids displayed differing tolerances to shade, (Moss and Stinson, 1961; Earley et al., 1966). These differential responses were attributed

to variations in the silking process, such as time of silk emergence, and not due to photosynthetic rates, growth, or disease. A study of several corn hybrids grown over a period of 41 months in Hawaii demonstrated that cyclical changes in grain yield were closely linked to changes in solar radiation. Higher incident light resulted in increased grain yields. These seasonal changes were due to day length, cloud cover, and shortening of the growing season due to high temperatures (Jong et al., 1982).

Photosynthetic rates per unit leaf area were not correlated to yield in sugarcane, and therefore should not be used as criteria for selection for yield. Photosynthetic rates per unit land area were found to be more closely related to yield. Higher leaf area indices and optimal leaf arrangement should therefore be the characteristics looked for in breeding for yield improvement. Similar results have been observed for other grasses, as well, including wheat and maize (Irvine, 1975).

Shading studies: Ornamentals, trees

Research concerning the effects of shading on ornamentals and tree seedling crops is important primarily for efficient greenhouse production or to better understand conditions in shaded habitats. Flower initiation in the hybrid geranium, Pelargonium x hortorum, was delayed three

weeks and the number and size of flowers reduced when shade
was 60% or greater (Armitage and Wetzstein, 1982). In
chrysanthemum, the rate of gross photosynthesis/unit leaf
area at light saturation increased with increasing
radiation integral. When expressed per unit leaf dry
matter, however, it was unaffected by growth radiation. A
greater percentage of dry matter was partitioned to stem
tissue at the expense of root tissue as radiation increased
(Acock et al., 1979). Rhododendron catawbiense cuttings
were rooted under 0, 55, and 95% shade in a greenhouse by
Davis and Potter (1983). Higher net photosynthetic rates,
water potentials, and carbohydrate levels which influenced
rooting were obtained with increasing light. Dark
respiration was unaffected by light. After two months of
growth at the different shade levels, however, no size
differences between treatments was observed. False aralia,
Dizygotheca elegantissima, was grown under 50 and
80% shade. Carbohydrate levels were higher in shoots of
the 50% shade grown plants, with root carbohydrate levels
forming a larger percentage of total carbohydrates in the
80% shade treatments. The 80% shade treatment also
displayed a lower light compensation point and higher
levels of N, P, and K, but lower Mg and Ca levels compared
to the 50% shade treatment (Elliott et al., 1981).

In Hawaii, shading is used to provide a "suitable" growing environment for many of the crops of the ornamentals industry, including dendrobium orchids, potted plants, and anthuriums (Williamson and Wong, 1984; Williamson, 1987). As the floriculture industry expands in Hawaii, so does the area under shade, with an average increase of 37 acres per year. Traditionally, a shadehouse design of woven shadecloth suspended from post and cable structures was used in Hawaii, but with the introduction of knitted shadecloth, stronger and more flexible shadehouse designs are gaining acceptance.

Yellow birch seedlings (Betula alleghaniensis) were exposed to heavy (86%), moderate (72%), or no shade. The shaded seedlings grew more in height and leaf area and could better utilize light than those grown under full-sun. The full-sun seedlings accumulated more total dry weight, but the percent dry weight in the partially shaded seedlings was greater in the leaves and stems (Gordon, 1969). The allocation of dry matter between leave, stem, and roots was influenced relatively little by shading treatments imposed on Eucalyptus grandis seedlings. The utilization of dry matter by the stem and leaves of shaded seedlings was affected, though, with greater areas/unit weight of leaf and greater lengths/unit weight of stem occurring (Doley, 1978). Loach (1967, 1970) studied the shade tolerances of five different temperate tree seedling

species and found all species to possess some degree of adaption ability to shade. Tolerance was displayed by lower rates of leaf respiration and lower light compensation points. He concluded that differences in rates of respiration may be the most important determinants of success or failure in wooded habitats, where low light intensities may predominate.

Shading studies: Fruit tree crops

The shading responses of a number of tree crops have been extensively studied due to the importance of obtaining large yields of high quality fruit. In general, it has been found that light interception and light levels are very important in fruit production. Several researchers have worked with the effects of shading in apple trees. Jackson (1970) studied the effects of artificial shading on 'Cox's Orange Pippin' apple trees and found that apple fruit of high commercial quality did not develop on parts of the tree receiving less than 50% total incident radiation. Fruit size and proportion of fruit surface which had red coloration were negatively affected by this amount of shade. The color of 'Red Delicious' and 'McIntosh' apples was also determined by the amount of sunlight received (Heinicke, 1966). Best color was

obtained when fruit received 70 to 100% full-sun, with adequate color obtained under 40 to 70% full-sun. Fruit receiving less than 50% sun were smaller sized. The size, firmness, and acidity of the fruit were related to the exposure of the surrounding foliage which supplied the fruit with photosynthates. A shade of less than 64% full daylight also reduced apple fruit set, while increasing P, K, and B levels and reducing Ca and Mg levels in the shoots (Jackson and Palmer, 1977; Doud and Ferree, 1980; Proctor and Crowe, 1983). The shading of apple trees below a critical level thus can cause a multitude of problems, including suppression of dry weight accumulation, specific leaf weight, leaf number, net photosynthesis, and a lowering of fruit quality. The effect of shade on apple trees was similar whether it was in the form of continuous low illumination or alternating periods of full-sun and dense shade. This implies that apple tree growth depends on the total amount of accumulated photosynthetically active radiation rather than the level of light intensity (Barden, 1977).

Shading in nectarine and peach trees had similar effects as shade on apple trees. In peach, shading decreased stem diameter, increased leaf area, decreased specific leaf weight, and caused more horizontal leaf orientation. The previous light microclimate of the peach tree could influence the ability of the leaves to

photosynthesize; in other words, preconditioning light levels determined net photosynthesis later (Kappel and Flore, 1980, 1983). The quality of light received is also important in peach production for causing different responses. The 600 to 690 nm range is needed for leaf bud burst and the 500 to 600 nm range enhances flower bud opening (Kappel et al., 1983). Limiting the photosynthesis of nectarine trees increased fruit abscission, and seed discoloration, leading to reduced fruit number and fruit weight at harvest. Peaches and nectarines appear to be more sensitive to shade than apples, for already at 90% full-sun, negative effects were observed (Byers et al., 1984).

The increasing importance of kiwifruit production in the U.S. has led to studies concerning shade responses of this fruit tree. The shade leaves and sun leaves of kiwifruit responded in a manner similar to leaves of other plants which have been characterized, in that variations exist in leaf morphology, physiology, and photosynthetic responses between the two leaf types (Grant and Ryugo, 1984b). As expected, kiwifruit growing on shaded shoots were smaller, shoot dry matter decreased, and winter survival of buds formerly shaded was lower than for buds not shaded (Grant and Ryugo, 1983, 1984a).

Cacao, coffee, and tea crops traditionally have been viewed as species requiring shade for optimal productivity. However, recent research has indicated that cacao trees grown under no shade yielded three times as much as shaded trees over a 17 year period of continuous cropping (Murray and Nichols, 1966; Ahenkorah et al., 1974). For full productivity, these no-shade trees required more fertilizer and other inputs to prevent stress. This heavier bearing led to a decline in the economic life of the tree and could lead to more pest damage caused by "heavy bearing stress". If the nutritional needs of the cacao plant cannot be fully met, higher yields are obtained under partially shaded conditions (Cunningham and Burridge, 1960).

Shade trees are commonly planted together with coffee, tea, and cacao to provide shade and also shelter against heavy rain or wind and to stabilize soil, leaf, and air temperatures around the crops. Shading of these crops is also beneficial during periods of drought by lowering water requirements. The reduced light causes, as expected, morphological and physiological adaptations in the plants allowing for more efficient use of lower light levels. More dry matter is accumulated in the leaves as opposed to the roots and the leaf structures are altered so as to better utilize incident light and transmit less of it. An adjustment to shade is made by an increased ability to utilize short term increases in irradiance above the level

of the growth irradiance (Huxley, 1967; Willey, 1975; Friend, 1984).

The shade provided by trees in tea plantations is very unevenly distributed over the tea bushes, with the most lightly shaded row receiving up to 28 times more sunlight than the most heavily shaded one (Hadfield, 1974). This means the amount of sunlight received can vary from 35 to 94% full-sun, depending on the location of the bush in relation to the shade trees. Shade may be beneficial to tea plants not because of photosynthetic considerations, but rather because the altered leaf morphology caused by the shade is a desirable economic characteristic.

Shading studies: Vegetables

The number of vegetable crops on which shading studies have been undertaken is relatively small. Responses of yields and quality in relation to light levels have been particularly poorly studied. Much of the work that has been done has been carried out on legumes such as peas and beans. Lockhart (1961) found the optimal light intensities for maximum stem growth in 'Pinto' beans to occur at 40,000 lux. Lower growth rates occurred at light intensities greater or less than this level. He attributed the high intensity light inhibition and low energy red light

inhibition to the same step in the gibberellin system. Broad bean seedlings grown at reduced light intensities had reduced internode length and reduced cell multiplication. As light intensities were increased, cell multiplication increased, leading to increased leaf area; cell enlargement was less sensitive to changes in light (Butler, 1963). Similar results were obtained in studies with green gram plants (Phaseolus aureus) (Monsi et al., 1962).

Sale (1974) studied the effect of the high solar energy incidence present in New South Wales, Australia on the growth of French beans. The plants light saturated at 600 to 650 $W \cdot m^{-2}$, which was much less than the amount of radiation which they received. Once the critical leaf area index was achieved, the maximum photosynthetic rate of the crops was approximately constant for most of the period of measurement. Cabbages were also tested at this location and were found to saturate at 800 $W \cdot m^{-2}$, still less than the total amount of solar radiation available. The high plant productivity observed was most likely not due to the high rates of net photosynthesis possible under the high solar inputs, but rather due to high temperatures and a frost free environment.

For soybeans, saturating light intensity and maximum photosynthetic rate are a function of the light intensity received during growth. Leaves grown at low light intensities saturated at low light intensities and had low

maximum rates of photosynthesis. This indicates that
soybeans acclimate to their light environment, developing
sufficient but not excessive photosynthetic capacity to
utilize the maximum available light (Bowes et al., 1972).
Reduced light levels can reduce grain yield, however.
Several cultivars of soybeans were planted over three years
in several locations in Hawaii to test yield variation over
gentoypes, locations, and seasons. Although differences
were observed between genotypes and between locations, best
yields were obtained from plantings in January, May, and
September (Beard et al.; Beard et al., 1980). Reduced
incident light levels due to cloud cover and shorter days,
and high temperatures were implicated in causing reduced
yields at certain times of the year. 'Kahala' soybean,
cowpea (Vigna unguiculata Walp.) and bushbean were grown in
Paia, Hawaii under shadecloth producing 0, 30, 55, and
73% shade throughout the entire crop cycle (Eriksen and
Whitney, 1984). Plantings were carried out in April and
November. Relative shading effects were similar over both
seasons, although absolute yields were lower in the fall
planting. This was attributed to daylength and temperature
sensitivity in soybean and cowpea. Cowpea was the least
shade tolerant of the three crops studied, while soybean
seed yields and dry matter content from plants grown under
30% shade were similar to the no shade treatment. Bushbean

was the most shade tolerant, producing maximum yields under 30% shade.

Peanuts also were found to be very sensitive to both reductions in available photosynthetically active radiation and high temperatures (Hang et al., 1984). 'Florunner' peanut was shaded during different developmental stages and yield components tested. A 75% reduction of solar radiation intensity reduced yields significantly only when the duration of shading lasted more than 14 days. Flower number, peg development, pod formation, and dry matter accumulation were all negatively affected, but not to the same extent. Two Virginia-type cultivars were grown in controlled environment chambers at quantum flux densities of 230 or 650 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Plants grown under the higher irradiance level accumulated three times more dry matter, fixed three times more nitrogen, and had a greater reproductive potential compared to plants grown under the lower light level (Farnham et al., 1986). Optimum temperatures for most peanut genotypes are near 30°C, with higher temperatures causing reduced individual leaf areas and dry weights, reduced total leaf area, and reduced number of subterranean pegs. Mature seed weights were also negatively affected by high temperatures (Ketring, 1984).

Shading of green field peas resulted in a significant decrease in seed weight and yield, and a significant increase in the protein content of the seed. This higher

protein content resulted in a poorer cooking quality due to the longer cooking time required (Gubbels, 1981). Pea fruits contribute to their own growth through photosynthesis and therefore have a role in determining yield (Hole and Scott, 1981).

Onions seeded in a greenhouse in Illinois received either incident sunlight or incident sunlight supplemented by artificial light (530 to 750 nm). This supplemental light increased the photosynthetic photon flux density by 17% on sunny days. More dry weight was produced by both shoots and roots in the supplemental light treatments (Whiteside et al., 1975). Soil temperatures of $29^{\circ}C$ caused earlier maturation of onion bulbs but lower yields compared to $18^{\circ}C$ and $24^{\circ}C$. Soil (bulb) temperatures lower than $18^{\circ}C$ reduced both top and bulb growth (Yamaguchi et al., 1975).

Sale (1974) carried out similar studies with white potatoes as he had with French beans and cabbage. Light saturation of the potato plant was achieved at 400 to 450 $W \cdot m^{-2}$ with little or no further uptake occurring even though solar incidence was up to 1000 $W \cdot m^{-2}$. Thus the potatoes light saturated at half full sunlight. Net photosynthesis in potato plants is determined by the size of the sink provided by the developing tubers. Another study with potato placed the plants under 34% shade until tubers had formed. Then the plants either received full-sun or a continuation of shade. Shade for half the

lifecycle of the potato caused reduced numbers of tubers, while continual shade reduced the maximum bulking rate achieved. The best yields were obtained under sequential conditions of full-sun, partial shade, and full-sun (Sale, 1976).

Studies with sweet potato indicate that this plant light saturates at levels below full sunlight, therefore a slight reduction in light levels would have little or no effect on productivity (Moreno, 1980). Very low light intensities, however, reduce the extent of photochemical processes such as photosynthesis and light induced movements and can cause changes in photoperiodism or light induced germination. Sweet potatoes vary tremendously in their ability to produce under mild shade, but no cultivars have yet been identified which can perform well under heavy shade. Martin (1985) suggested that cultivars which yield well in full-sun are also more likely to yield well in shade. Thus shade tolerance could be considered a part of general adaptation.

Cocoyams grown under 50% shade yielded only 1/4 (grown under Inga vera trees) to 1/2 (grown under plantains) of tubers compared to those grown under full-sun; corm yields were not significantly affected by shade. However, shading helped prevent attack of the plant by the "mal seco" fungus, probably due to reduced moisture present from transpiration (Rodriguez-Garcia et al., 1981).

The growth rate of bell pepper seeds and fruit wall plus placenta was not affected by the covering or uncovering of the fruits, nor were seed dry weight or nitrogen content in the fruit wall plus placenta affected. The only apparent effect of shading of bell pepper fruits was a 15% decline in fruit weight (Achhireddy et al., 1982). Solanum nigrum, the black nightshade (a vegetable crop in Southeast Asia) was subjected to shading studies by Fortuin and Omta (1980). Shade caused a decline in total plant weight and changes in the distribution of biomass. Shade retarded fruiting and shortened the duration of fruit production. However, the production of edible leaves was not affected by light shade (35 to 45%) and only moderately by heavy shade (95%). Leaf morphology was affected by shade but palatability was improved through the use of shade.

The effect of 15, 30, and 40% shade from plastic tunnels and shadehouses on tomatoes and cucumbers grown in South Africa was investigated by Smith et al. (1984). Full sun radiant flux density reached 750 $W \cdot m^{-2}$ and unshaded plot air temperatures reached 28°C. Shading reduced not only incident light, but also air temperatures. Shaded crops had greater leaf areas, smaller root systems, and increased resistance to leaf water movement. Shaded cucumbers had reduced fruit yields, with proportionately greater amounts of photosynthates put into leaves and

stems. Tomato plants, however, produced the highest fruit yields under 15% shade, compared to no shade, 30%, or 40% shade.

Chinese cabbage (Brassica campestris spp. pekinensis) usually performs poorly when grown under high temperatures and high photosynthetic photon flux densities. A study carried out in Taiwan during such environmental conditions tested the possible beneficial effects of shading and leaf-tying 30 days after transplanting. Shading caused reduced yields in all cases. Leaf-tying of a moderately heat-tolerant cultivar doubled yields compared to the control by producing heavier heads and higher heading rates. Leaf-tying apparently reduced internal head temperatures and shaded newly formed leaves, without causing a reduction of photosynthetic rate (Sajjapongse and Roan, 1983).

Heat tolerant and heat sensitive Chinese cabbage cultivars displayed similar responses to temperature and daylength changes, but the critical temperature for bolting was much higher for the tolerant lines. A significant interaction between temperature and daylength was observed, with shorter days causing less bolting. Lengthening the time of exposure to higher temperatures (above 18°C for heat sensitive and above 24°C for heat tolerant cultivars) also reduced bolting incidence (Krug and Kling, 1982; Guttormsen and Moe, 1985a, 1985b; Moe and Guttormsen, 1985).

Several studies have been undertaken to determine how reduced solar radiation incidence in the winter months in temperate regions would affect lettuce production. Gray and Morris (1978) studied differences in the weather which might influence lettuce growth and time to maturity in the United Kingdom. They found that lettuce crop growth was not simply related to either radiation or temperature. Growth in the early stages of plant development prior to hearting was largely affected by temperature, while after hearting occurred radiation was more important. At temperatures above 11-12°C and total radiation above 250 mWh·cm^{-2}, growth and time to maturity were little affected by variations in either. A similar study carried out in the Netherlands also showed that temperature was most influential in the early stages of lettuce growth, with radiation mainly influencing time to harvest and dry matter production (Bierhuizen et al., 1973). The importance of the temperature and radiation interaction was also emphasized. In both the studies of Bierhuizen et al. (1973) and Gray and Morris (1978), lettuce productivity was directly correlated with increases in either temperature or solar radiation incidence. Verkerk and Spitters (1973) conducting phytotron studies, concluded that the greater the light energy received, the less critical the temperature in relation to lettuce growth.

Two cultivars of leaf lettuce were exposed to photosynthetic photon flux densities of 444 or 889 $\mu mol \cdot s^{-1} \cdot m^{-2}$ and differing temperature regimes. Leaf dry weight of both cultivars was higher when grown under high light intensities and warm temperatures, and lowest under low light intensities coupled with cooler temperatures (Knight and Mitchell, 1983). Miller and Langhans (1985) found that diurnal fluctuation of temperatures influenced productivity of 'Grand Rapids' lettuce. Plants performed well when air temperatures were increased from $15^{o}C$ to $35^{o}C$ or increased to $35^{o}C$ then decreased to $25^{o}C$, but did poorly when the temperature was decreased from $35^{o}C$ to $15^{o}C$ over a 16 hour period. They concluded that early day high temperatures should be avoided for optimum productivity. Warmer soil temperatures, achieved by various soil mulches and differing dates of sowing, resulted in faster relative growth rates, but had small effects at maturity (Wurr et al., 1981).

In another study carried out in the U.K., lettuce plants were either shaded (50% full-sun) from the time of emergence to the beginning of hearting or conversely, from the time of hearting to maturity. It was observed that early shading lengthened the outer non-hearting leaves by 12% but reduced the length of the inner leaves. This caused a decreased head weight but had no effect on head volume. Plants which were shaded in the later stages of

their development were increased in volume and displayed no reduction in head weight (Gray and Steckel, 1981).

The quality of Cos lettuce grown in Israel was found to be dependent to a large extent on soil temperatures. The best head development occurred at soil temperatures between 12°C and 28°C, with abnormal head development occurring when soil temperatures were 36°C. At this high temperature, leaf folding, twisting, and drying occurred more rapidly. High air temperatures were also indicated in producing fewer leaves and causing rapid bolting (Nothmann, 1977a, 1977b).

Glenn (1984) carried out a greenhouse study in Arizona to determine the effect of radiation and temperature on lettuce growth in a desert environment. He found that there was an interaction between day temperatures and radiation in influencing growth, but that the extent of this interaction was seasonally determined. Growth of plants in the autumn was more influenced by radiation, while in the spring temperature had a greater effect on growth. This was explained as being due to higher radiation levels in the spring. Day temperatures up to 30°C accelerated growth, while the number of days to harvest was strongly correlated with radiation up to 55 cal$\cdot$cm$^{-2}\cdot$day^{-1}. In general, the growth curves had the same shape as the radiation curves, with a four week lag time between the two.

In a second experiment carried out in Arizona, Glenn et al. (1984) studied the effects of artificial shade imposed on lettuce and spinach plants in a greenhouse. Photosynthetically active radiation (PAR) transmission levels of 8 to 75% were used. In both lettuce and spinach, the control plants grew faster than the shaded ones. However, lettuce and spinach were both found to grow at very low light levels, 8 $mol \cdot m^{-2} \cdot day^{-1}$ producing marketable yields. The most productive plants in terms of growth rates and market quality grew under high PAR levels, however. The researchers concluded that lettuce saturates at a PAR level above 40 $mol \cdot m^{-2} \cdot day^{-1}$ (full-sun), while spinach saturates at 25 $mol \cdot m^{-2} \cdot day^{-1}$ (60% full-sun), the best spinach being produced under 25-30% shade. Plants grown under very low light levels did not form heads and produced more ground cover per unit weight.

Mattei et al. (1973) grew two different lettuce cultivars in a field trial in England and in Italy under 30, 50, and 70% full sunlight. The lettuce saturated under relatively low levels of radiation, with 50% full sunlight producing the best results. Radiation optima were between 100 and 200 $cal \cdot cm^{-2} \cdot day^{-1}$ depending on the cultivar, with growth inhibition actually occurring at intensities above 450 $cal \cdot cm^{-2} \cdot day^{-1}$. They concluded that shade treatments would be especially beneficial where irrigation is necessary, since the evaporation rate is reduced under shade.

CHAPTER III

PRODUCTIVITY OF FIVE TROPICAL VEGETABLE CROPS

GROWN UNDER SHADE IN HAWAII[1]

Introduction

The decreasing availability of good agricultural land and the high costs of land and agricultural inputs are becoming serious limiting factors to increased agricultural production in a number of areas, especially in the tropics (Stelly, 1983). These problems necessitate the development of agricultural systems that use land more intensively without adversely affecting quality or yield. Mixed-cropping, the practice of growing several crops on the same piece of land, either simultaneously or in succession, is an intensive land-use method with the potential for increasing food production (ICRISAT, 1981). Shading among plants, as occurs when vegetable crops of different heights are grown together or when short stature crops are grown within orchard stands, becomes a major consideration in a mixed-crop situation.

Studies of the effects of reduced photosynthetic photon flux (PPF) on vegetable crop productivity have shown great variability in responses of leaf and plant morphology, productivity, and physiology among and within crop species. These responses depend on several factors including cultivar, the quality and quantity of radiation under which a crop was grown, the light saturation point of the leaf canopy, and other environmental conditions, especially temperature (Bowes et al., 1972; Ketring, 1984;

Knight and Mitchell, 1983; Martin, 1985; Smith et al., 1984).

Under tropical and subtropical conditions, yields and quality of vegetable crops have been improved by shading. For example, tomatoes, spinach, and lettuce yielded more under reduced PPF conditions ranging from 15% to 50% shade in regions with high light intensities (Glenn et al., 1984; Mattei et al., 1973; Smith et al., 1984). Therefore, both mixed cropping and crop production under shade structures have potential for increasing productivity of vegetable crops in the tropics and subtropics. This study was undertaken to evaluate the effects of five artificially produced shade levels on the productivity of five tropically important vegetable crops grown in Hawaii.

<u>Materials and Methods</u>

<u>Field preparation.</u> A 0.12 ha field at Waimanalo Agricultural Research Station, Oahu, Hawaii was prepared for planting in the summer of 1986. Local recommendations for soil preparation and fertilization for eggplant, soybean, peanut, sweet potato, and lettuce were followed at all times (Beard et al., 1980; Hartmann et al., 1978; Tanaka and Sakuoka, 1973). Triple superphosphate (0N-20P-0K), dolomitic limestone, and urea were added to

the Typic Haplustoll subgroup type soil to raise the soil solution P concentration to 0.3 $\mu g \cdot ml^{-1}$ (Nishimoto et al., 1977), the pH from 5.4 to 5.9, and to add an equivalent of 60 kg N/ha to the field. For the Spring 87 trial, the field was reworked and refertilized with 1345 $kg \cdot ha^{-1}$ of 16N-7P-13K.

Experimental design. Shadecloth canopies were erected over each of 15 plots. Supports were 10 cm x 10 cm x 3 m wooden beams set at the corners of 7.6 m x 9.1 m plots and anchored 1 m deep in the soil in a grid-shaped pattern. Galvanized 0.6 cm diameter wire rope was strung between the beams 1.8 m above the ground, and grometted panels of commercially available, black shadecloth were suspended from the wire rope. Three replicates of each of four shade levels (30%, 47%, 63%, and 73%) were completely randomized in the field. Maximum and minimum air temperatures, precipitation, and total solar irradiance (SI) under full-sun were monitored daily using a LICOR LI-1200 datalogger equipped with a thermistor temperature sensor, tipping-bucket rain gauge, and an LI-200SA pyranometer (Fig. 3.1).

Total SI ($MJ \cdot m^{-2} \cdot crop^{-1}$) was converted to total photosynthetically active radiation (PAR - $mol \cdot m^{-2} \cdot crop^{-1}$) using the conversion for sunlight determined by Meek et al. (1984). Total PAR was used in discussing yield results rather than total SI after it was determined with a LICOR
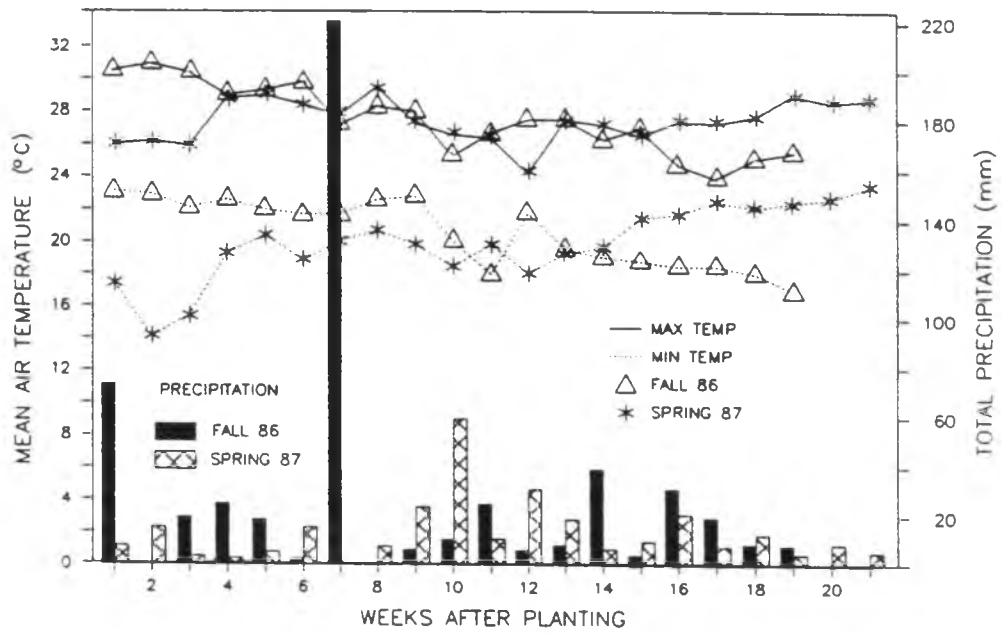
Fig. 3.1. Mean weekly minimum and maximum air temperatures and total weekly precipitation during Fall 86 and Spring 87.

LI-191SA Line Quantum Sensor that PAR was directly proportional to the level of shade used. PAR was used rather than SI because of uncertainty about the effect of shade on short and long wave irradiance. Total PAR received by each crop was used instead of percent shade because total PAR received varied among crops and seasons, and percent shade as a predictor variable would not reflect these differences.

Cultural conditions. Five rows of 'Waimanalo Long' eggplant, and four rows each of 'Kahala' soybean, 'Jumbo Virginia' peanut, 'Waimanalo Red' sweet potato, and 'Green Mignonette' lettuce, known locally as "Manoa lettuce", were grown simultaneously in each plot. Crop subplots were randomized within each shade level plot to minimize border effects. Data were collected only from the two or three internal rows in crop subplots. The study was carried out twice, from Sept 86 to Feb 87 and from Feb 87 to July 87.

Eggplant was seeded 10 Aug 86 (Fall 86) and 8 Jan 87 (Spring 87) into transplant flats with 5-cm-diameter cells that contained a mixture of 1 peat : 1 vermiculite (by volume) amended with 271 g dolomite and 139 g gypsum per m^3. Micronutrients and slow release nutrients were incorporated as 33 g Micromax and 1109 g Osmocote (19N-6P-12K) (Sierra Chemical, Milpitas, CA) per m^3, respectively. Dates of transplanting of the eggplant

seedlings and 0.3 m long sweet potato cuttings, and of the
direct-seeding of soybean, peanut, and lettuce, the dates
of harvest, cultural parameters, and experimental plot
sizes are presented in Table 3.1. The final spacing
(Table 3.1) was achieved by thinning the direct-seeded
crops three weeks after planting. All plants were
fertilized by banding 1345 kg·ha^{-1} of 16N-7P-13K fertilizer
four weeks after planting. The plots were drip-irrigated
three times per week at an average rate of 0.5 cm·day^{-1} to
supplement natural rainfall. All plots were irrigated
equally regardless of shade level. Very heavy rains during
Fall 86, especially during the week of 9 Nov 1986
(Fig. 3.1), eliminated the need for subsequent irrigation.
Weeding was done by hand as required. Pest control
practices were used as required.

Leaf area and dry weight measurements. In order to
determine characteristics of leaf morphology as influenced
by shading, three young, fully expanded index leaves per
subplot were collected for leaf area and leaf dry weight
measurements. Eggplant, soybean, and peanut index leaves
were collected at anthesis, sweet potato index leaves at
the beginning of bulking, and lettuce index leaves at
harvest maturity. Leaf area was measured using a LICOR
LI-3100 Area Meter. Leaves were dried for at least 48 hr
at 65°C before weighing.

Table 3.1. Planting and harvest dates and cultural parameters for 'Waimanalo Long' eggplant, 'Kahala' soybean, 'Jumbo Virginia' peanut, 'Waimanalo Red' sweet potato, and 'Green Mignonette' lettuce grown during Fall 86 and Spring 87.

Crop	Planting date Fall 1986	Planting date Spring 1987	Harvest date Fall 1986[x]	Harvest date Spring 1987	No. of plants row^{-1}	Spacing between rows	Spacing between plants	No. rows	Plot size
Eggplant	26 Sept	17 Feb	27 Jan[z]	9 Jun[z]	5	0.7 m	0.7 m	5	4.8 m^2
Soybean	2 Oct	17 Feb	13 Jan	26 May	35	0.7 m	0.1 m	4	5.4 m^2
Peanut	2 Oct	17 Feb	3 Feb[y]	8 July[y]	20	0.6 m	0.2 m	4	9.7 m^2
Swt. potato	3 Oct	24 Feb	28 Jan[z]	25 Jun[z]	12	0.9 m	0.3 m	4	13 m^2
Lettuce	2 Oct	22 Feb	18 Nov	14 Apr	15	0.3 m	0.2 m	4	2.2 m^2

[z] Final harvest date.

[y] Full-sun harvest date.

[x] Dates are 1987 with exception of lettuce which is 1986.

Photosynthesis data. Photosynthesis data were collected for all crops under all shade levels to investigate the influence of shading on net photosynthesis (Pn). Rates of Pn in two young, fully expanded leaves were determined in situ in all subplots using a LICOR LI-6000 Portable Photosynthesis System equipped with a quantum sensor (LI190-SA) to measure photosynthetic photon flux (PPF - $\mu mol \cdot m^{-2} \cdot s^{-1}$). Data were taken during the spring planting only. Photosynthetic data for eggplant, soybean, and peanut were taken at anthesis, sweet potato data at the beginning of bulking, and lettuce data at harvest maturity. The leaf-leaf chamber orientation during the measurements corresponded to the pre-measurement leaf angle. Ten readings 6 seconds apart per measurement were taken between 1000 hr and 1400 hr during bright sky conditions. A continuous range of PPF and Pn rates resulted from cloud cover varying while measurements were made among the plots.

Harvest procedures. Mature eggplant fruit were harvested, counted, and weighed fresh weekly. The duration of the harvest periods for the Fall 86 and Spring 87 plantings were 11 and eight weeks, respectively. Soybeans were harvested when 50% of the plants had 95% of their pods brown (harvest maturity) (Jones, 1985). The plants were dried completely, threshed, and total dry seed weights measured. Peanuts were harvested at harvest maturity (50%

of the plants with 2/3 to 3/4 of all developed pods having testa or pericarp coloration) (Jones, 1985). Pods and seeds were cleaned and dried and total pod plus seed dry weights recorded.

Successive, destructive harvests of entire sweet potato plants were made beginning eight weeks after planting in Fall 86, with a total of four harvests at two and a half week intervals. Shoot and root fresh weights and numbers of roots from six plants were measured at each harvest. Vine length of three randomly selected vines/subplot also was determined. Because beginning of bulking first occurred about 11 weeks after cuttings were planted in Fall 86, the first harvest in Spring 87 was made at this time. Subsequent harvests were scheduled two weeks apart to obtain four harvests in the same total growing time as in Fall 86.

Successive, destructive harvests of lettuce were made weekly, beginning four weeks after seeding (Fall 86) and five weeks after seeding (Spring 87) in order to observe differences in growth rates and physiological maturity between shade treatments. At each harvest four lettuce heads were cut from the two center rows of each subplot and total head fresh weights measured. The criterion for harvest maturity was the development of compact heads ("heading up").

Best-fit curves for leaf area, dry weight, harvest yield, and photosynthetic rate vs. shade, estimated PAR, or PPF were calculated using polynomial models with the System for Statistics (Wilkinson, 1986). Only coefficients significant at $P < .05$ were retained in the models.

Results and Discussion

Leaf morphology. Specific leaf area (index leaf area/index leaf dry weight - SLA) of eggplant, soybean, and lettuce increased as percent shade increased (Fig. 3.2) because index leaf areas were constant while leaf dry weights declined as shade increased. This increase in SLA with decreasing shade was observed in both seasons with these three crops. The production of broad, thin leaves is a common characteristic of plants growing in natural shady environments, because it increases the light interception possible per unit of structural biomass (Boardman, 1977).

Peanut and sweet potato SLAs were unaffected by shade in either Fall 86 or Spring 87, but for different reasons. Peanut index leaf area and dry weight were both significantly reduced by shading, while index leaf area and dry weight of sweet potato were unchanged over all shade levels tested. Individual sweet potato vine length also was not affected by shade, while total plant top fresh weight was significantly reduced under shade in both
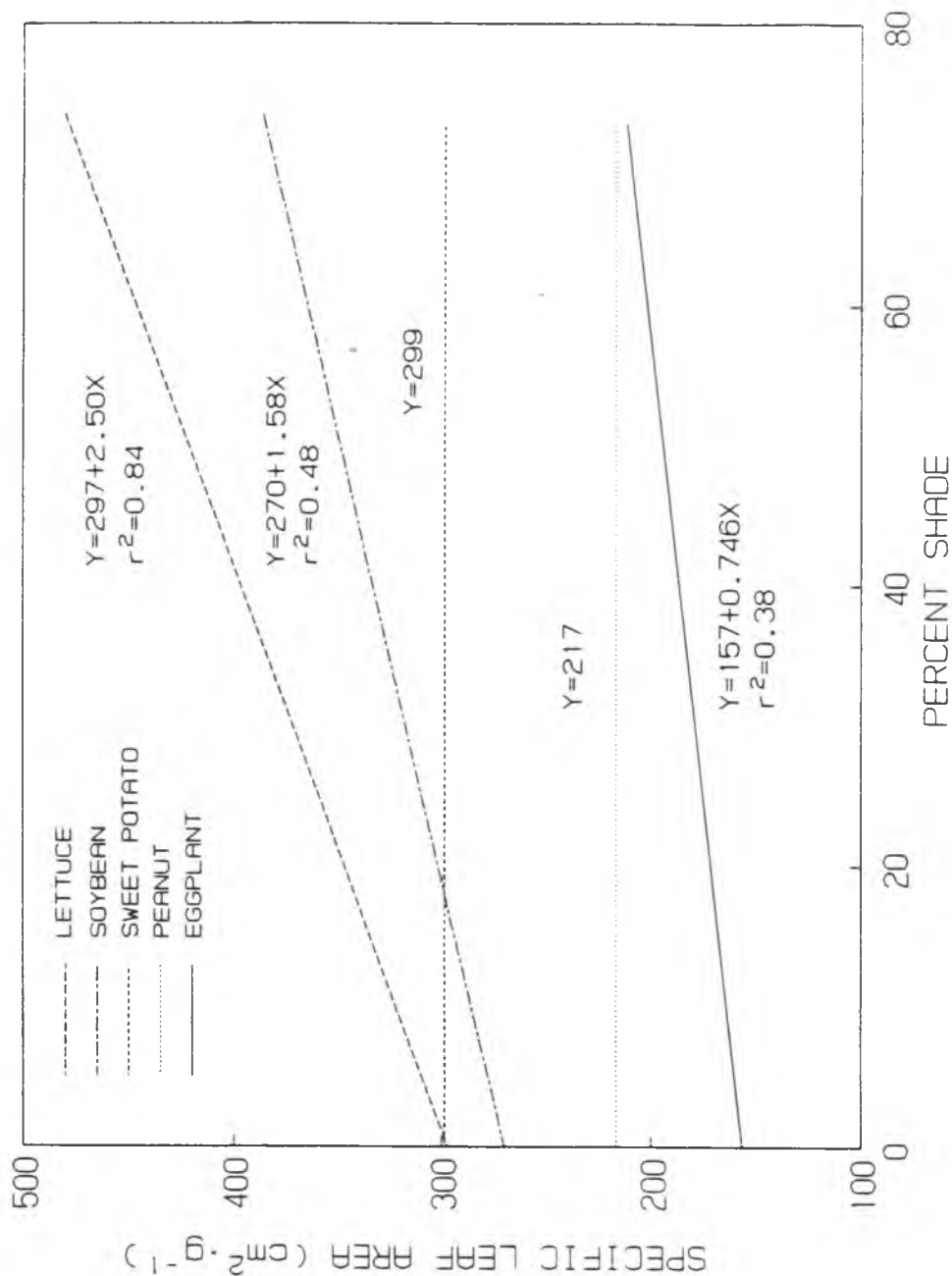
Fig. 3.2. Specific leaf area of 'Waimanalo Long' eggplant, 'Kahala' soybean, and 'Jumbo Virginia' peanut, at anthesis, 'Waimanalo Red' sweet potato at beginning of bulking, and 'Green Mignonette' lettuce at harvest maturity averaged over both experiments as a function of percent shade.

experiments (Table 3.2). Because shade had no effect on vine length but a significant effect on plant top fresh weight, it was concluded that the total number of vines per plant was reduced by shading.

Photosynthetic rates. Net carbon assimilation rates of eggplant, soybean, peanut, and sweet potato increased linearly up to the highest PPF observed with full sunlight (approximately 2200 $\mu mol \cdot s^{-1} \cdot m^{-2}$) (data not shown). Maximum photosynthetic rates for eggplant, soybean, and sweet potato were about 18 $\mu mol \ CO_2 \cdot m^{-2} \cdot s^{-1}$, and for peanut about 24 $\mu mol \ CO_2 \cdot m^{-2} \cdot s^{-1}$ at 2200 $\mu mol \cdot s^{-1} \cdot m^{-2}$.

Lettuce responded differently to increasing light levels, with maximum Pn of approximately 10 $\mu mol \ CO_2 \cdot m^{-2} \cdot s^{-1}$ reached at about two-thirds of full sunlight (1500 $\mu mol \cdot s^{-1} \cdot m^{-2}$) (Fig. 3.3). Conclusions about the effects of higher light intensities on lettuce Pn are not possible from these data due to high variability. Light saturation at half of full sunlight and decreased photosynthetic rates at higher light intensities have been reported previously (Mattei et al., 1973).

Development and yields. Cumulative eggplant fruit yields from the 11 weekly harvests in the fall and eight weekly harvests in the spring increased linearly with increasing total PAR (Fig. 3.4A). Reduced fruit set under shade appeared to be responsible for most of the decrease

Table 3.2. Vine length, plant top fresh weight, cumulative root number, and mean single root weight of 'Waimanalo Red' sweet potato grown during Fall 86 and Spring 87 under 5 shade levels.

Percent shade	Single vine length (cm)		Plant top fresh weight ($MT \cdot ha^{-1}$)		Cumulative root number ($x10^3 \cdot ha^{-1}$)		Mean single root weight (g)	
	Fall 86	Spring 87	Fall 86	Spring 87	Fall 86	Spring 87	Fall 86	Spring 87
0	221 (24)[z]	69 (5)	77.2 (6.3)	53.9 (3.6)	63 (5)	124 (3)	62 (15)	118 (22)
30	198 (21)	64 (8)	62.8 (2.8)	55.0 (4.1)	45 (6)	129 (12)	64 (11)	101 (9)
47	220 (18)	67 (4)	55.1 (3.1)	43.3 (3.1)	37 (11)	92 (16)	70 (22)	68 (15)
63	197 (24)	66 (9)	34.0 (3.5)	33.4 (2.6)	12 (7)	49 (14)	56 (24)	42 (6)
73	198 (21)	59 (5)	31.1 (1.5)	28.9 (3.1)	10 (6)	30 (10)	29 (10)	43 (10)
Sig.								
Linear	NS[y]	NS	**	**	**	**	NS	**
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS

[z] ±95% confidence interval.

[y] NS, *, **, *** Nonsignificant (NS) or significant at 5% (*), 1% (**), or 0.1% (***) levels.
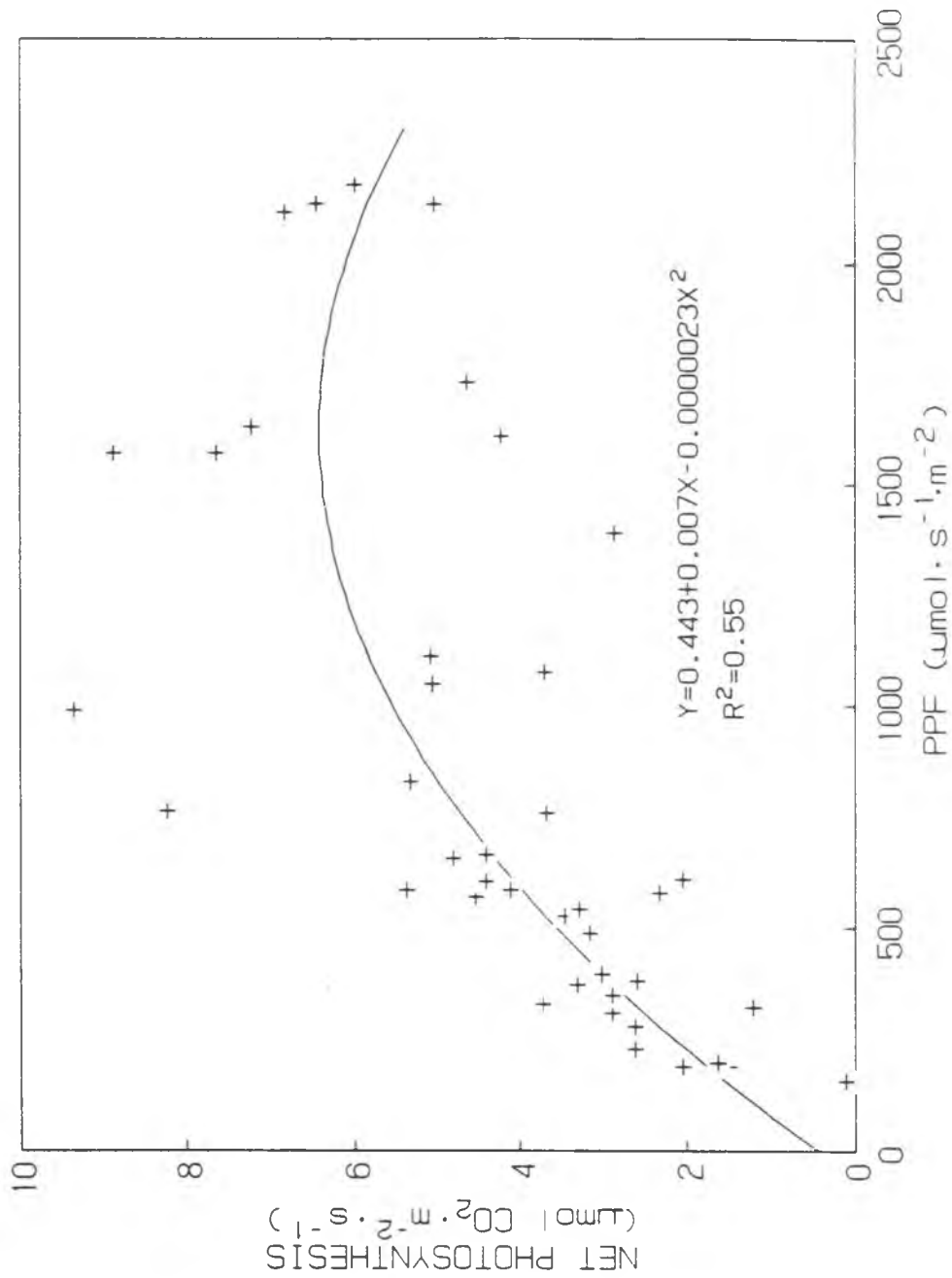
Fig. 3.3. Photosynthetic rate of 'Green Mignonette' lettuce at harvest maturity during Spring 87 as a function of PPF.
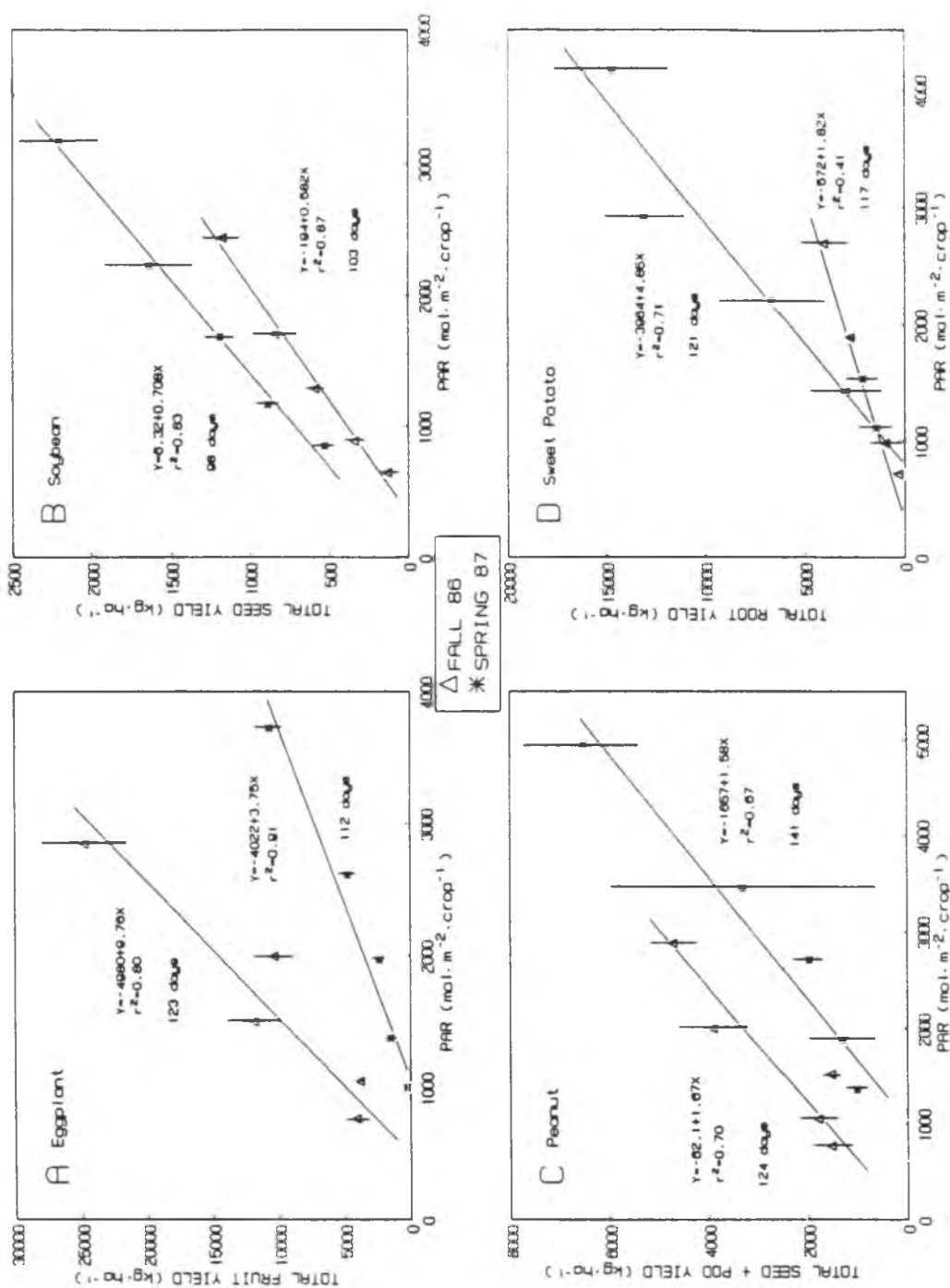
Fig. 3.4. Total fruit yield of 'Waimanalo Long' eggplant (A), total seed yield of 'Kahala' soybean (B), total seed + pod yield of 'Jumbo Virginia' peanut (C), and total root yield of 'Waimanalo Red' sweet potato (D) grown during Fall 86 and Spring 87 as a function of accumulated PAR·crop^{-1}. Days indicated is length of crop cycle. Vertical bar represents SE of the mean.

in yields because total fruit number was reduced by reduced light levels relatively more than mean single fruit weights (Table 3.3).

In Fall 86, anthesis was delayed from three days under 30% shade to 14 days under 73% shade compared to plants grown in the full-sun (Table 3.3). In Spring 87, anthesis was delayed three days under all shade levels compared to full sunlight. These delays in anthesis caused corresponding delays in time to first fruit harvest. First harvest in the full-sun plots began four weeks after transplanting in the fall, but six weeks after transplanting in the spring.

Regardless of shade level, the peak harvest occurred 11 weeks after transplanting in the fall, and 10 weeks after transplanting in the spring. Likewise, the final harvest, determined when fruit yields and quality had declined sharply, was made 14 and 13 weeks after tranplanting, for the fall and spring experiments, respectively (Table 3.1). This decline occurred in the same week in all shade levels in both experiments. A three week longer harvest period in Fall 86 produced higher eggplant yields overall in this experiment compared to Spring 87. Full-sun yields for Fall 86 were similar to yearly island of Oahu averages of 26,600 kg·ha^{-1}, while Spring 87 yields were only 40% of those averages (Hawaii Agricultural Statistics Service, 1986).

Table 3.3. Cumulative fruit number, mean single fruit weight, and date of anthesis of 'Waimanalo Long' eggplant grown during Fall 86 and Spring 87 under 5 shade levels.

Percent shade	Cumulative fruit number $(\times 10^3 \cdot ha^{-1})$		Mean single fruit weight (g)		Date of anthesis	
	Fall 86	Spring 87	Fall 86	Spring 87	Fall 1986	Spring 1987
0	458 (51)[z]	239 (19)	53.9 (1)	45.1 (2)	4 Nov	7 April
30	241 (35)	108 (15)	43.4 (1)	45.5 (1)	7 Nov	10 April
47	218 (22)	57 (10)	54.0 (4)	44.3 (1)	13 Nov	10 April
63	92 (2)	42 (9)	42.2 (1)	37.0 (1)	15 Nov	10 April
73	96 (20)	12 (3)	43.3 (2)	29.5 (4)	18 Nov	10 April
Sig.						
Linear	**[y]	**	*	**		
Quadratic	NS	**	NS	*		

[z] ±95% confidence interval.

[y] NS, *, **, *** Nonsignificant (NS) or significant at 5% (*), 1% (**), or 0.1% (***) levels.

Higher yields in the Fall 86 than in the Spring 87 plantings probably were due to the fact that 'Waimanalo Long' eggplant was bred in Hawaii and is adapted to the warmer fall temperatures (Tanaka and Sakuoka, 1973). The mean maximum air temperature for the first half of the crop cycle of eggplant was $29.3^{\circ}C$ during Fall 86 compared to $27.7^{\circ}C$ during Spring 87, while the mean minimum air temperature was $22.4^{\circ}C$ in Fall 86 compared to $18.3^{\circ}C$ in Spring 87 for the same periods (Fig. 3.1).

Soybean yields also were very sensitive to shade (Fig. 3.4B). Unlike eggplant, soybean seed yields were higher in the spring than in the fall. Lower yields of 'Kahala' soybean have been reported previously for the period from August to December (Beard et al., 1980; B. Beard, S. Geng, and R. Hartmann, unpublished data; Eriksen and Whitney, 1984). Shading studies carried out with 'Kahala' soybean in Paia, Hawaii resulted in similar seed yields in the no-shade plots and 30% shade plots, while darker shade reduced yields (Eriksen and Whitney, 1984). In contrast to yields, physiological development of the soybean plants in both the fall and spring trials was not influenced by shading. The 4-nodes stage, anthesis, green-bean stage, and harvest maturity all occurred at the same time in all shade treatments (Table 3.1).

Peanut total seed-plus-pod yields also decreased with decreasing total PAR received (Fig. 3.4C). Development also was delayed by shade stress, with anthesis delayed three days under 47% shade and five days under 63% and 73% shade in Fall 86. In Spring 87, anthesis was delayed two days under 30% and 47% shade, and 12 days under 63% and 73% shade. This delay in anthesis caused corresponding delays in time to harvest (Table 3.1). Peanut is very sensitive to temperatures above 25°C, which cause reduced vegetative and reproductive growth (Hang et al., 1984; Ketring, 1984). The lower yields of peanut during the fall compared to the spring planting may have been due to the warmer temperatures experienced at that time (Fig. 3.1).

Total root yields of 'Waimanalo Red' sweet potato also were directly reduced by shading in both seasons (Fig. 3.4D). As with soybean and peanut, sweet potato yields were higher in the spring than in the fall. Fall 86 yields under full-sun were only 33% of seasonal state averages, while Spring 87 yields were similar to seasonal state averages of 11,600 kg·ha^{-1} (Hawaii Agricultural Statistics Service, 1986). These yield differences between Fall 86 and Spring 87 probably were due to premature harvesting in fall compared to spring. Both mean single root weight and number of roots were reduced with reduced

total PAR for any one harvest (Table 3.2). 'Waimanalo Red' appears to be less shade tolerant than other reportedly shade-adapted cultivars whose root yields were equal to or greater than full-sun plot yields when grown under 20% shade (Martin, 1985).

In contrast to the other crops, lettuce yields were not significantly reduced by moderate shading (Fig. 3.5). On the contrary, reducing total PAR by 30% appeared to be beneficial to the fall crop, increasing yields 40% relative to the crop grown in the open-sun. Yields were 27% higher in the 47% shade treatment compared to the full-sun treatment. Heavy shade (63% and 73% shade) reduced not only total yields, but also the quality of the heads by producing loose heads with fewer leaves.

The beneficial effect of 30% and 47% shade on 'Green Mignonette' lettuce during the fall is most likely due to an alleviation of high temperature and/or water stress while still providing enough radiant energy for maximum Pn. This cultivar is known to perform better under temperatures cooler than those predominating during the fall crop (Hartmann et al., 1978). Mean maximum air temperature for the growing period of lettuce (seven weeks) in the fall was 29.3^{o}C, compared to 27.9^{o}C during the spring. Mean minimum air temperatures were 22.2^{o}C in the fall and 18.4^{o}C in the spring (Fig. 3.1).
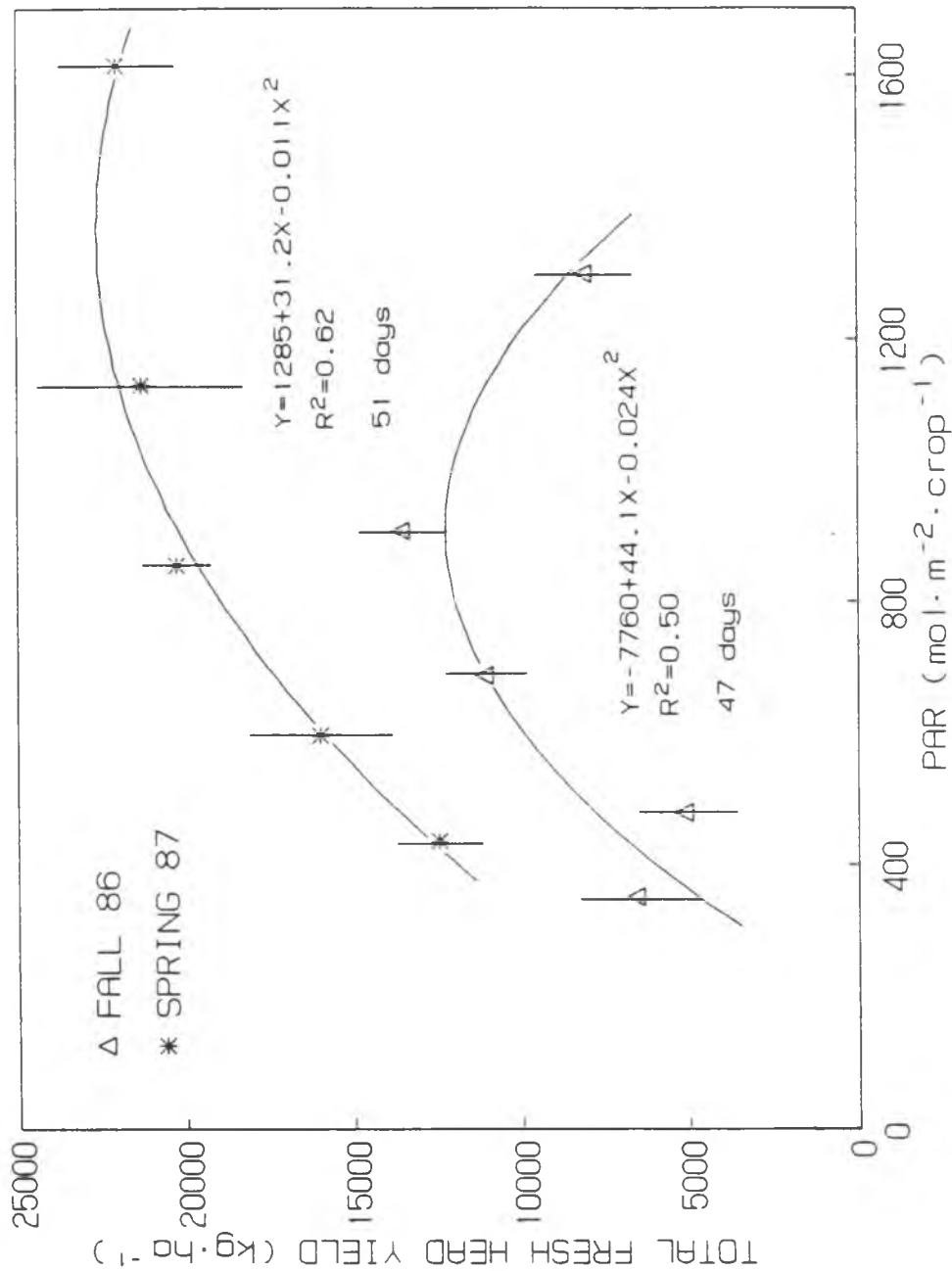
Fig. 3.5. Total fresh head weight yield of 'Green Mignonette' lettuce grown during Fall 86 and Spring 87 as a function of accumulated PAR·crop^{-1}. Days indicated is length of crop cycle. Vertical bar represents SE of the mean.

During Spring 87, yields were much higher at all shade
levels than during Fall 86, presumably because of cooler
temperatures. Yields in the spring under 30% and 47% shade
were as high as with no shade, although no enhancement of
yields by these levels of shade was observed. Thus, while
shade may not be beneficial, neither is it detrimental,
during cooler seasons. Low quality, lightweight heads were
again produced under 63% and 73% shade as in the fall.
Seasonal differences in yield usually occur in commercial
lettuce production, with island of Oahu lettuce yields in
November being 16% lower than those harvested in April
(Hawaii Agricultural Statistics Service, 1986). The
average yield over both experiments of the full-sun plots,
15,000 $kg \cdot ha^{-1}$, was slightly higher than the yearly island
average of 14,000 $kg \cdot ha^{-1}$. Growth rate was similar under
all shade treatments during both seasons, with all plants
reaching maturity simultaneously. One week after harvest
maturity plants had begun to bolt regardless of shade
level.

The results of this study indicate that 'Waimanalo
Long' eggplant, 'Kahala' soybean, 'Jumbo Virginia' peanut,
and 'Waimanalo Red' sweet potato have no potential for
yield improvement by shading, while the yields of
'Green Mignonette' lettuce grown under "light" (30 to 47%)
shade are similar to or increased significantly compared to
full-sun plots. The beneficial effects of shade on lettuce

yield appear to be related to the mitigation of high temperature and/or water stress.

For eggplant, soybean, peanut, and sweet potato, any reduction in light level resulted in a decrease in net photosynthesis, while light shade did not cause a reduction in lettuce Pn. Thus of these five crops, only the lettuce could be grown under lightly shade conditions and still receive enough radiant energy for maximum Pn. Based on these results, it appears that only 'Green Mignonette' lettuce has potential for being grown successfully in shaded environments such as in multiple cropping situations. Intercropping studies using this lettuce cultivar should be carried out, however, to confirm these present shading trials.

CHAPTER IV

PRODUCTIVITY OF EIGHT LEAFY VEGETABLE CROPS
GROWN UNDER SHADE IN HAWAII

Introduction

Production of temperate leafy green vegetables such as
lettuce and members of the genus <u>Brassica</u> is most often
carried out in cool environments with low solar radiation
(Glenn, 1984). In tropical and subtropical regions this
limits production to highland areas and the lowland tropics
during the cool season. Photosynthetic photon flux (PPF)
is considerably higher in tropical compared to temperate
regions (Glenn, 1984; Sajjapongse and Roan, 1983; Sale,
1975; Smith et al., 1984) resulting in higher temperatures
and higher evapotranspirative demands (Doorenbos and
Pruitt, 1977; Morris et al, 1957). Poor head formation,
leaf twisting, early bolting, and reduced yields have been
reported to occur when temperate leafy vegetables are grown
under hot, high sunlight conditions (Nothmann, 1977a;
Sajjapongse and Roan, 1983; Wurr et al., 1981). Water
stress caused by high evapotranspirative demand, and high
air and soil temperatures appear to be the main causes of
poor crop productivity of leafy crops in low latitude
regions (Nothmann, 1977a; Wurr et al., 1981; Yamaguchi et
al., 1975).

A previous study in Hawaii demonstrated that shading
reduced yields of eggplant, soybean, peanut, and sweet
potato. Yields of semihead lettuce were unchanged or
increased with 30% shading (Chapter III). The present

study was undertaken to evaluate the effects of five artificially produced shade levels on yield, vegetative, and photosynthetic components of a wider range of leafy vegetable crops grown in Hawaii.

Materials and Methods

Field preparation. A 0.17 ha field at Waimanalo Agricultural Research Station, Oahu, Hawaii was prepared for planting in the summer of 1987. Local recommendations for soil preparation and fertilization for lettuce, Chinese cabbage, mustard cabbage, head cabbage, and bunching onions were followed at all times (Hartmann et al., 1978a, 1978b; Takeda and Sakuoka, 1979). The Typic Haplustoll subgroup type soil was amended with 842 kg·ha^{-1} of 10N-13P-8K. The soil was fumigated with 200 kg·ha^{-1} methyl bromide to control weeds. For Spring 88, the field was reworked and refertilized as for Fall 87.

Experimental design. Shadecloth canopies were erected over each of 25 plots. Supports were 10 cm x 10 cm x 3 m wooden beams set at the corners of 7.6 m x 9.1 m plots and anchored 1 m deep in the soil in a grid-shaped pattern. Galvanized 0.6 cm diameter wire rope was strung between the beams 1.8 m above the ground, and grometted panels of commercially available, black shadecloth were suspended

from the wire rope. Five replicates of each of four shade
levels (30%, 47%, 63%, and 73%) were completely randomized
in the field. Minimum and maximum air temperatures were
monitored daily using min-max thermometers and soil water
tension was monitored daily with tensiometers placed at
18 cm depths under all five shade levels for the duration
of both experiments. Soil temperatures under 0, 47, and
73% shade were monitored daily over a two week period
during Spring 88 using thermistors placed at 10 cm depths
and an Omnidata Intl. EL-824 datalogger. Evaporimeters
described previously (Ekern, 1983) were used to monitor
daily evaporation under full sunlight and 73% shade.
Precipitation and total solar irradiance (SI) under full-
sun were monitored daily using a LICOR LI-1200 datalogger
equipped with a tipping-bucket rain gauge and an LI-200SA
pyranometer.

Total SI ($MJ \cdot m^{-2} \cdot crop^{-1}$) was converted to total
photosynthetically active radiation (PAR - $mol \cdot m^{-2} \cdot crop^{-1}$)
using the conversion for sunlight determined by Meek et al.
(1984). Total PAR was used in discussing yield results
rather than total SI after it was determined with a LICOR
LI-191SA Line Quantum Sensor that PAR was directly
proportional to the level of shade used. PAR was used
rather than SI because of uncertainty about the effect of
shade on short and long wave irradiance. Total PAR

received by each crop was used instead of percent shade because total PAR received varied among crops and seasons, and percent shade as a predictor variable would not reflect these differences.

Cultural conditions. Six 4-m-long rows each of 'Green Mignonette' (a semihead type known locally as "Manoa"), 'Salinas', 'Amaral 400', and 'Parris Island Cos' lettuce, 'WR-55 Days' Chinese cabbage, 'Waianae Strain' green mustard cabbage, 'Tastie Hybrid' head cabbage, and an unnamed local selection of bunching onions were grown simultaneously in each plot. Crop subplots were randomized within each shade level plot to minimize border effects. Data were collected only from the four internal rows in crop subplots. The study was carried out twice, from Aug 87 to Oct 87 and from April 88 to June 88.

The head cabbage was seeded 22 June 87 (Fall 87) and 9 April 88 (Spring 88) into transplant flats with 5-cm-diameter cells that contained a mixture of 1 peat : 1 vermiculite (by volume) amended with 271 g dolomite and 139 g gypsum per m^3. Micronutrients and slow release nutrients were incorporated as 33 g Micromax and 1109 g Osmocote (19N-6P-12K) (Sierra Chemical, Milpitas, CA) per m^3, respectively. Dates of transplanting of the head cabbage seedlings and the bunching onion sets, and of the direct-seeding of the other six crops, along with dates of

harvest, number of plants per row, and between- and within-row spacing are presented in Table 4.1. The final spacing (Table 4.1) was achieved by thinning the direct-seeded crops three to four weeks after planting. Experimental plot size for all crops was 1.2 m x 4.0 m. In the fall, 'Salinas' and 'Green Mignonette' lettuce seed germinated very poorly and plots for these crops were reseeded 8 and 15 Sept 87, respectively. The second planting of 'Salinas' was successful, but again 'Green Mignonette' did not germinate. All plants were fertilized by banding 842 kg·ha^{-1} of 10N-13P-8K four weeks after planting. The plots were drip-irrigated three times per week at an average rate of 0.5 cm·day^{-1} to supplement natural rainfall. All plots were irrigated equally regardless of shade level. Weeding was done by hand as needed. Pest control practices were used as required.

Leaf area and dry weight measurements. In order to determine characteristics of leaf morphology as influenced by shading, three young, fully expanded index leaves per subplot were collected for leaf area and leaf dry weight measurements at harvest maturity. Leaf area was measured using a LICOR LI-3100 Area Meter. Leaves were dried for at least 48 hr at 65°C before weighing.

Table 4.1. Planting and harvest dates and cultural parameters for four cultivars of lettuce, 'WR-55 Days' Chinese cabbage, 'Waianae Strain' green mustard cabbage, 'Tastie Hybrid' head cabbage, and a local unnamed selection of bunching onions grown during Fall 87 and Spring 88.

| Crop | Planting date | | Harvest date | | No. of plants row^{-1} | Spacing between rows | Spacing between plants |
	Fall 1987	Spring 1988	Fall 1987	Spring 1988			
'Green Mignonette'	18 Aug[z]	28 April	---	9 June	15	30 cm	24 cm
'Salinas'	8 Sept[y]	28 April	30 Oct	14 June	15	30 cm	24 cm
'Parris Island Cos'	18 Aug	28 April	6 Oct	16 June	15	30 cm	24 cm
'Amaral 400'	18 Aug	28 April	13 Oct	14 June	15	30 cm	24 cm
Chinese cabbage	18 Aug	28 April	13 Oct	7 June	12	30 cm	30 cm
Mustard cabbage	18 Aug	28 April	6 Oct	7 June	12	30 cm	30 cm
Head cabbage	18 Aug	3 May	13 Oct	16 June	12	30 cm	30 cm
Bunching onion	19 Aug	3 May	13 Oct	14 June	15[x]	30 cm	24 cm

[z] Replanted 15 Sept.

[y] 18 Aug planting did not germinate.

[x] Planted as doubles.

Elemental analysis of plant tissue. Three young, fully expanded index leaves per subplot were collected at harvest maturity in Fall 87 only. These samples were bulked according to crop type and shade treatment, and analyzed at the Agricultural Diagnostic Service Center, University of Hawaii for total nutrient content (Isaac and Johnson, 1976; Wallace and Barrett, 1981).

Photosynthetic data. Photosynthesis data were collected for all crops under all shade levels to investigate the influence of shading on net photosynthesis (Pn). Rates of Pn in two young, fully expanded leaves were determined in situ in all subplots using a LICOR LI-6000 Portable Photosynthesis System equipped with a quantum sensor (LI190-SA) to measure photosynthetic photon flux (PPF – $\mu mol \cdot m^{-2} \cdot s^{-1}$). Photosynthesis data for all crops were taken at harvest maturity during both experiments. Because of technical complications, data were taken during the spring planting only for 'Green Mignonette' and 'Salinas' lettuce and bunching onions. The leaf-leaf chamber orientation during the measurements corresponded to the pre-measurement leaf angle. Ten readings six seconds apart per measurement were taken between 1000 hr and 1400 hr during bright sky conditions. A continuous range of PPF and Pn rates resulted from cloud cover varying while measurements were made among the plots.

Harvest procedures. Total fresh head weights or fresh bunch weights (bunching onions) for all crops were taken at harvest maturity. The criterion for harvest maturity of the head crops was the development of compact heads ("heading up"), and for the bunching onions size of bunches. None of the crops were trimmed before weighing to avoid subjectively biasing the results.

Best-fit curves for leaf area, leaf dry weight, photosynthetic rate, and harvest yield vs. shade, PPF, or estimated PAR were calculated using polynomial models with the System for Statistics (Wilkinson, 1986). Seasonal comparisons were made by testing light by season interactions. Only coefficents significant at $P < .05$ were retained in the models.

Results and Discussion

Leaf morphology. Specific leaf area (index leaf area/index leaf dry weight - SLA) of 'Green Mignonette' and 'Amaral 400' lettuce, Chinese cabbage, green mustard cabbage, head cabbage, and bunching onions increased as percent shade increased due to reduction of index leaf dry weights by shading, while index leaf areas were maintained (Fig. 4.1A, B). This indicates a limited genetic ability for morphological adaptation to shade in these crops. The production of broad, thin leaves is a common characteristic
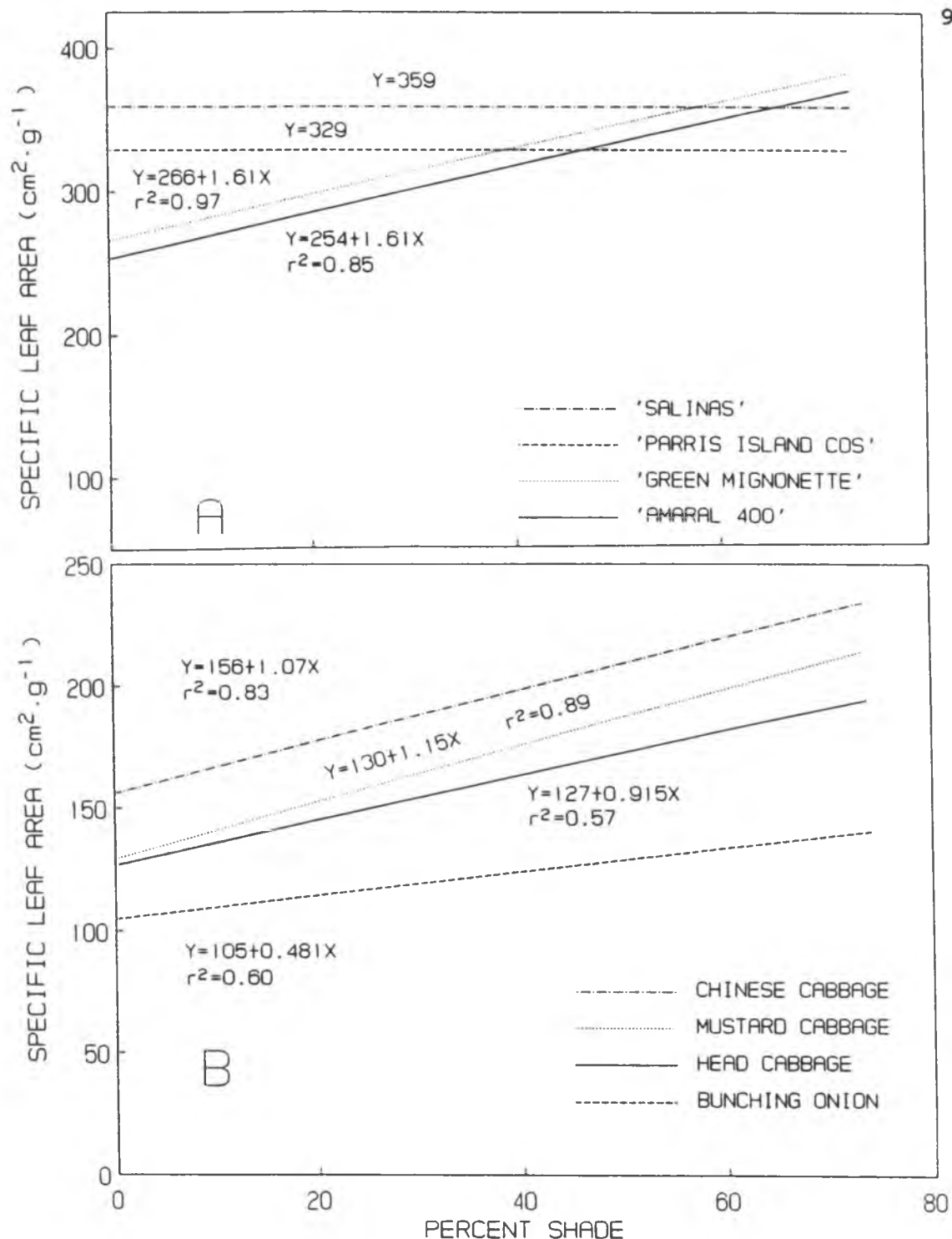
Fig. 4.1. Specific leaf area of 'Green Mignonette',
'Salinas', 'Parris Island Cos', and 'Amaral 400' lettuce
(A) and 'WR-55 Days' Chinese cabbage, 'Waianae Strain'
green mustard cabbage, 'Tastie Hybrid' head cabbage, and an
unnamed local selection of bunching onions (B) at harvest
maturity averaged over both experiments as a function of
percent shade.

of plants growing in natural shady environments, because it increases the light interception possible per unit of structural biomass (Boardman, 1977). The relationship of leaf dry weight to leaf area was similar in both seasons with these six crops. 'Salinas' and 'Parris Island Cos' lettuce SLA were unaffected by shade in either Fall 87 or Spring 88 because index leaf area and dry weight were not affected by shade level.

Elemental analysis of plant tissue. Shading had no effect on the elemental analysis of any of the nutrients tested, including nitrogen, in any of the crops examined (data not shown). Elemental analyses of the four lettuce cultivars indicated sufficient mineral nutrition based on published tissue content values (Lorenz and Tyler, 1983), and thus nutritional levels were assumed to be sufficient for the other leafy crops also.

Photosynthetic rates. Net carbon assimilation rates of 'Green Mignonette' lettuce increased linearly up to the highest PPF observed with full sunlight (approximately 2200 $\mu mol \cdot s^{-1} \cdot m^{-2}$); the maximum photosynthetic rate was about 12 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$ (Fig. 4.2A). Maximum net photosynthesis rates of 9 to 14 $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$ of 'Salinas', 'Parris Island Cos', and 'Amaral 400' lettuce, Chinese cabbage, green mustard cabbage, and head cabbage were reached between PPFs of 1500 and 1750 $\mu mol \cdot s^{-1} \cdot m^{-2}$
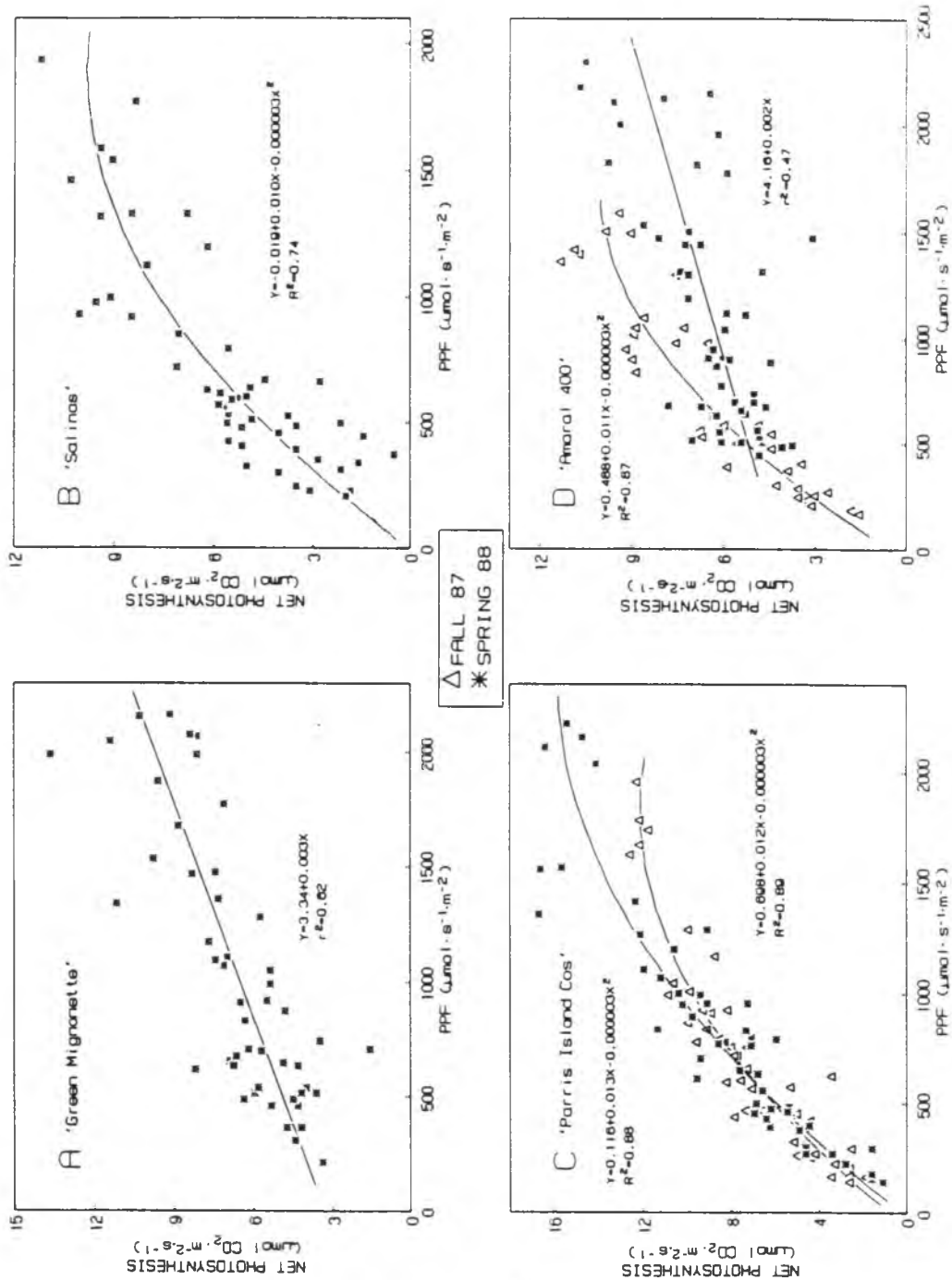
Fig. 4.2. Photosynthetic rates of four lettuce cultivars at harvest maturity during Fall 87 and Spring 88 as a function of PPF.

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(two-thirds to three-fourths of full sunlight) (Fig. 4.2B, C, D; 4.3A, B, C). Conclusions about the effects of higher light intensities on the Pn of these crops are not possible from these data. Light saturation of lettuce at two-thirds (1500 $\mu mol \cdot s^{-1} \cdot m^{-2}$) of full sunlight and of head cabbage at 1600 $\mu mol \cdot s^{-1} \cdot m^{-2}$ with decreased photosynthetic rates at higher light intensities have been reported previously (Chapter III; Mattei et al., 1973; Sale, 1975). Net photosynthesis rates of bunching onions did not respond to increasing light levels for the light intensities tested (Fig. 4.3D). Data were scattered between -10 $\mu mol \; CO_2 \cdot m^{-2} \cdot s^{-1}$ (net respiration) to 20 $\mu mol \; CO_2 \cdot m^{-2} \cdot s^{-1}$. Onions exhibit midday closure of stomata (Heath, 1969) which can account for this unresponsiveness of onion Pn to shading.

For the majority of the crops examined, "light" (30 to 47%) shade did not cause a reduction net photosynthesis. This indicates that these crops could be grown under lightly shaded conditions without adverse effects on maximum net photosynthesis.

Yields. Total fresh head yields of 'Green Mignonette' lettuce grown during Spring 88 were significantly increased 53% from 4700 kg·ha^{-1} for the crop grown in the open-sun to 7200 kg·ha^{-1} when total PAR was reduced by 47% (Fig 4.4A). A reduction of total PAR by 30% increased yields by 43%.
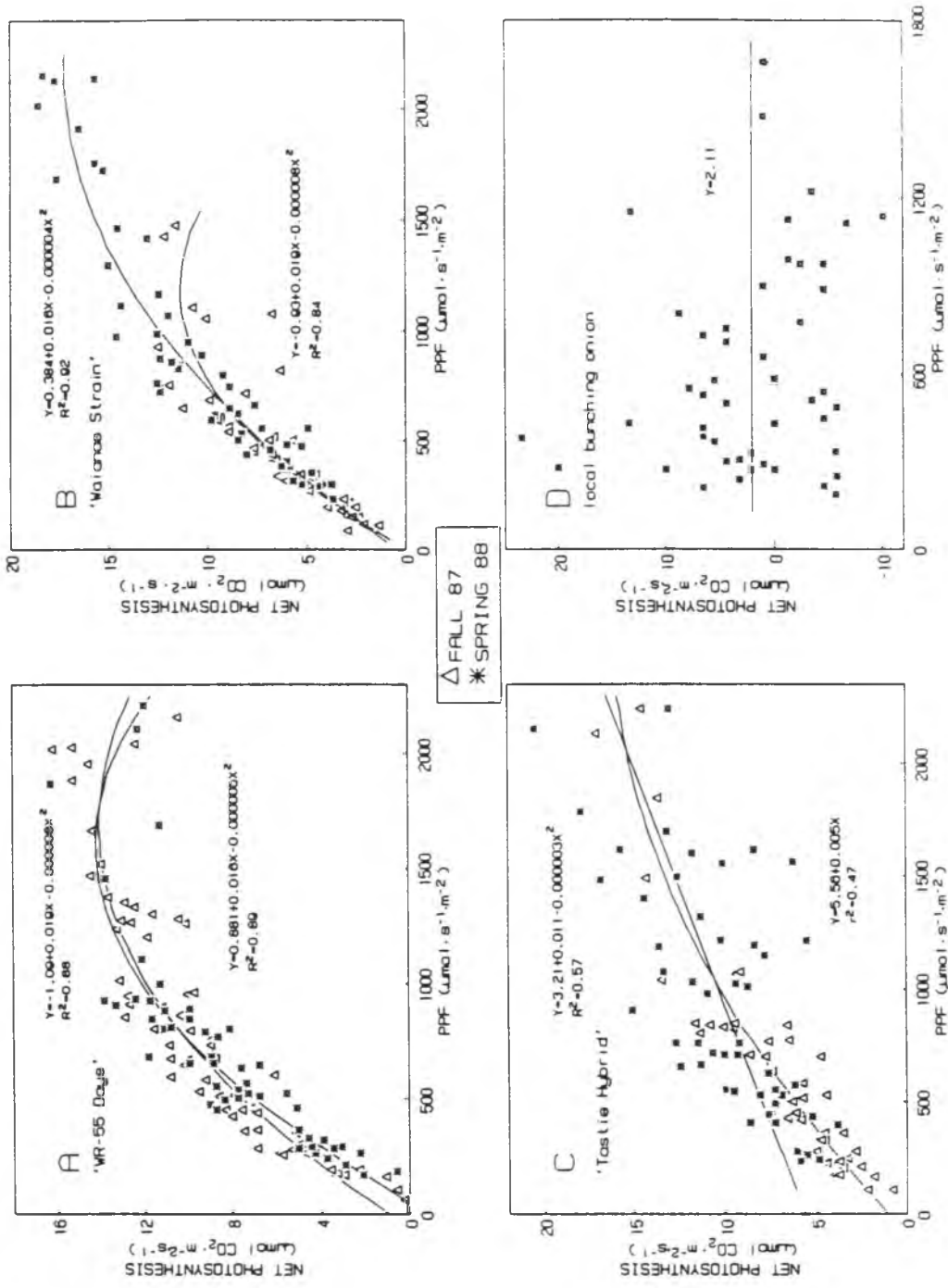
Fig. 4.3. Photosynthetic rate of 'WR-55 Days' Chinese cabbage (A), 'Waianae Strain' green mustard cabbage (B), 'Tastie Hybrid' head cabbage (C), and an unnamed local selection of bunching onions (D) at harvest maturity during Fall 87 and Spring 88 as a function of PPF.
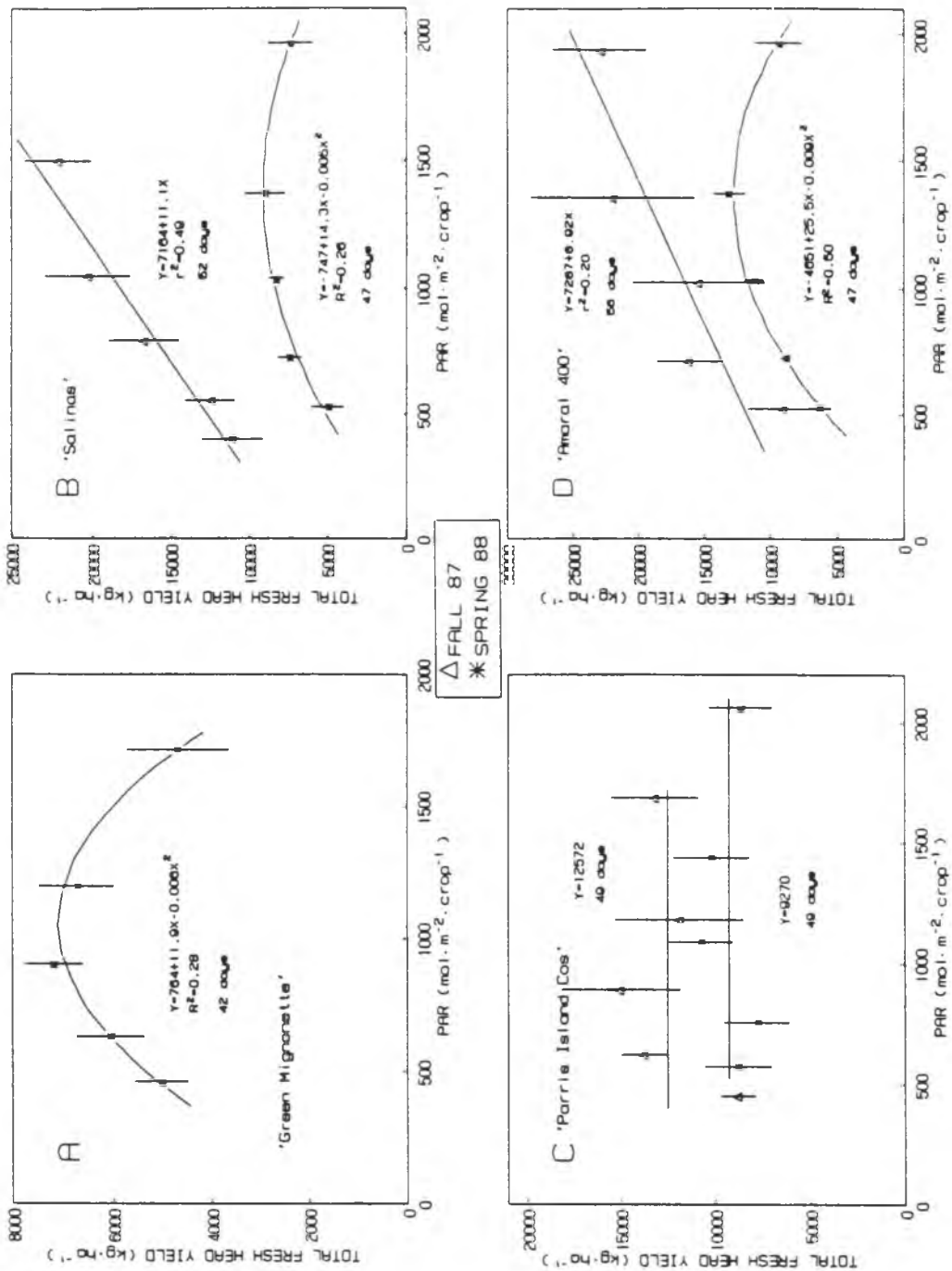
Fig. 4.4. Total fresh head weight yields of four lettuce cultivars grown during Fall 87 and Spring 88 as a function of accumulated PAR·crop^{-1}. Days indicated is length of crop cycle. Vertical bar represents SE of the mean.

Yields at 0 and 73% shade were comparable. However, overall yields were very low, with yields from the no-shade plots only 28% of island of Oahu averages for June (Hawaii Agricultural Statistics Service, 1986).

The germination failure of 'Green Mignonette' during Fall 87 and the low yields in Spring 88 were probably due to poor seed quality. Previous plantings of 'Green Mignonette' in the same field with a different seed lot had resulted in yields similar to state averages (Chapter III). There is no obvious explanation for these yield responses or the Pn rates increasing up to full-sun levels during this study; previous studies indicated that this cultivar attained maximum Pn at two-thirds of full sunlight (Chapter III).

In Fall 87, 'Salinas' and 'Amaral 400' lettuce yields decreased linearly with shading, while in Spring 88, yields of 'Salinas' and 'Amaral 400' lettuce were increased by 22% and 40%, respectively, in 30% shade (Fig. 4.4B, D). 'Parris Island Cos' lettuce yields did not respond to shading in either season (Fig. 4.4C). Lack of response to shade by this cultivar was apparently due to high variability within treatments in both seasons. Coefficients of variation for Fall 87 and Spring 88 were 43% and 42%, respectively. Averaged across seasons, full-sun yields of these three lettuce cultivars were similar to

yearly island averages of 14,000 kg·ha^{-1} for head lettuce
(Hawaii Agricultural Statistics Service, 1986).

Yields of 'WR-55 Days' Chinese cabbage were increased
by light shade in Fall 87 compared to full-sun plots, a 30%
reduction in total PAR received resulting in a 21% yield
increase (Fig. 4.5A). In Spring 88, however, yields
decreased linearly with increasing shade level. Seasonal
differences were not significant at the 5% level, however.
Yields obtained under full-sun were double those obtained
commercially on Oahu (Hawaii Agricultural Statistics
Service, 1986). This large difference between experimental
and commercial yields is most likely due to crop failures
being included in commercial yield calculations, as well as
some head trimming before weighing (S. Fukuda, personal
communication).

Fresh head yield of 'Waianae Strain' green mustard
cabbage decreased linearly with increasing shade in both
Fall 87 and Spring 88 (Fig. 4.5B). Overall yields were
higher in the fall compared to the spring, with a mean fall
yield nearly double the 19,300 kg·ha^{-1} harvested from the
full sunlight plots in the spring. Seasonal differences,
again, were not significant, however. These lower spring
yields were still greater than the 1986 island average of
12,800 kg·ha^{-1} for green mustard cabbage (Hawaii
Agricultural Statistics Service, 1986), probably for the
same reasons as those given for Chinese cabbage.

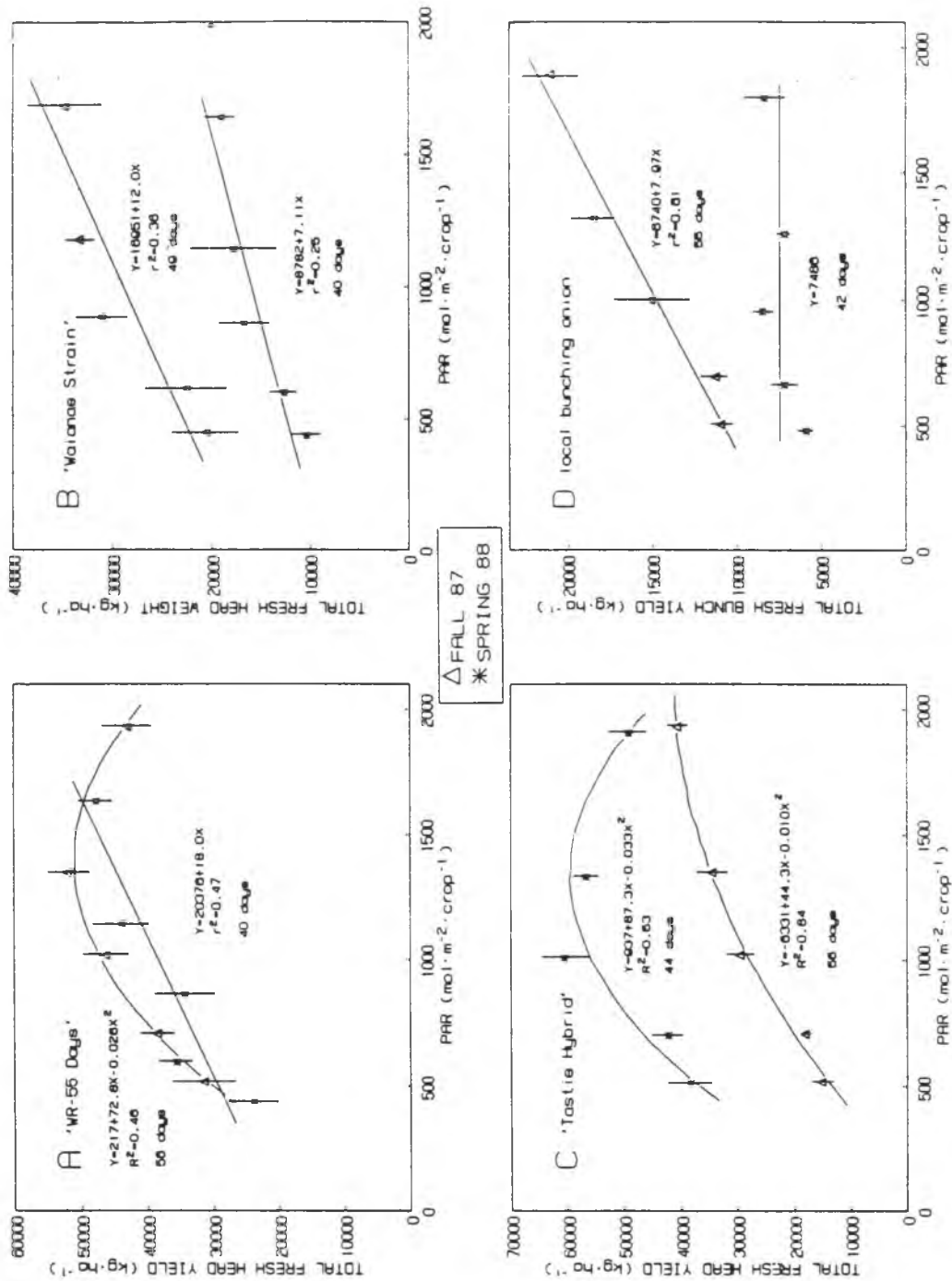Fig. 4.5. Total fresh head weight yield of 'WR-55 Days'
Chinese cabbage (A), 'Waianae Strain' green mustard cabbage
(B), 'Tastie Hybrid' head cabbage (C), and total fresh
bunch weight of an unnamed local selection of bunching
onions (D) grown during Fall 87 and Spring 88 as a
function of accumulated PAR·crop^{-1}. Days indicated is
length of crop cycle. Vertical bar represents SE of the
mean.

Head cabbage yields in Spring 88 were higher than Fall 87 yields, averaged across shade levels, although seasonal differences were not pronounced between fall and spring crops grown in the full-sun (Fig. 4.5C). Head cabbage yields under full sunlight in the fall and spring were 52% and 58% higher than island averages, respectively (Hawaii Agricultural Statistics Service, 1986). In the spring, shading up to 47% increased yields by 23% compared to the no-shade plots, while in the fall yields were reduced significantly by any amount of shading.

Bunching onion yields were reduced sharply by shading in Fall 87, while in Spring 88 yields did not respond to shading (Fig. 4.5D). Full-sun yields in Fall 87 were nearly three times greater than island averages for October, while Spring 88 yields were similar to island averages for June (Hawaii Agricultural Statistics Service, 1986).

During Fall 87, shading had no effect on soil water tension (Fig. 4.6) probably due to the abundant rainfall experienced in the fall compared to the spring (Fig. 4.7) and the consequent lack of supplemental irrigation. Soil water tension was significantly reduced by shading during Spring 88, however (Fig. 4.6). Leafy vegetables are very sensitive to moisture supply, water stress resulting in slow growth and tipburn (Hartmann et al., 1978a, 1978b; Takeda and Sakuoka, 1979). Some tipburn of all crops grown
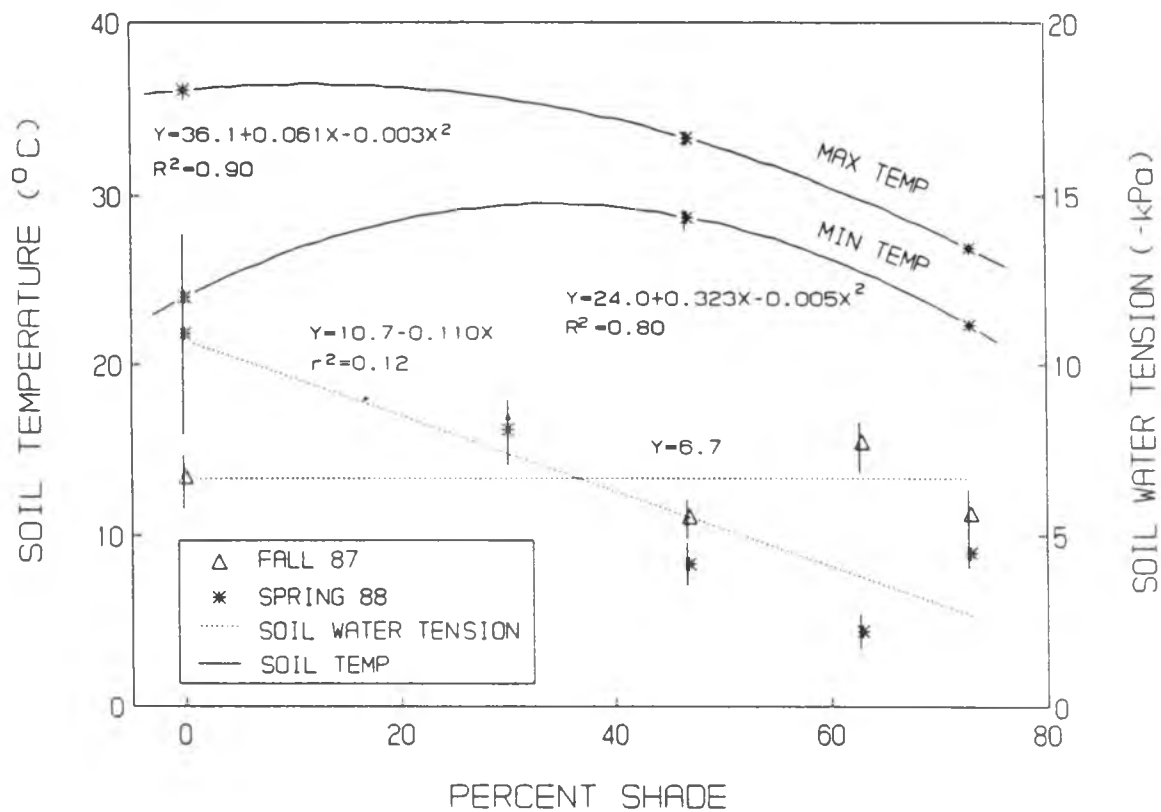
Fig. 4.6. Average minimum and maximum soil temperatures and soil water tension during Fall 87 and Spring 88 as a function of percent shade.
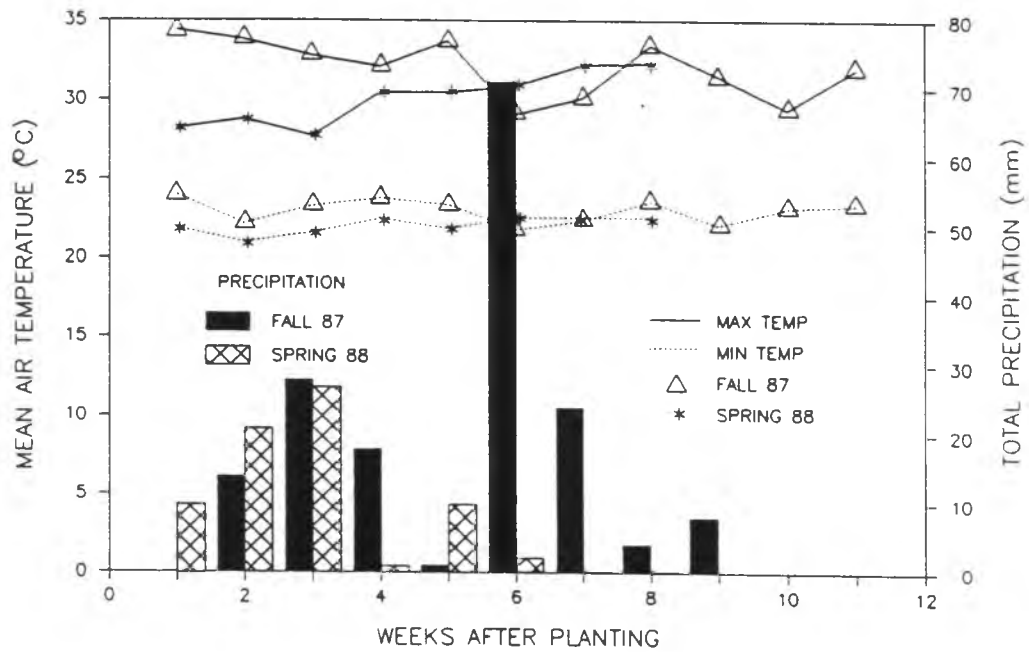
Fig. 4.7. Mean weekly minimum and maximum air temperatures and total weekly precipitation during Fall 87 and Spring 88.

in the full-sun plots except bunching onions was observed in the spring planting, although no quantitative data were taken. The reduction of soil water tension with shading during Spring 88 could account for the increased yields obtained under light shade with 'Green Mignonette', 'Salinas', and 'Amaral 400' lettuce (Fig. 4.2A, B, D) and head cabbage (Fig. 4.3C) compared to the full-sun plots during Spring 88. Shading by 63 or 73% was not beneficial for increasing yields, because PPF was reduced too much for optimum Pn.

Evaporation under the 73% shade canopy was reduced 36% in Fall 87 and 41% in Spring 88 compared to evaporation in full-sun (data not shown).

Shading reduced maximum air temperatures by about $1^{\circ}C$ per 15% increase in shade level. Minimum air temperatures were not affected by shade (data not shown). Shading also reduced maximum soil temperatures and prevented large diurnal fluctuations (Fig. 4.6). Maximum soil temperatures in Spring 88 were reduced from $36.1^{\circ}C$ under full-sun to $26.9^{\circ}C$ under 73% shade. A $12.1^{\circ}C$ difference between daytime and nighttime soil temperatures was recorded in open-sun plots, while maximum diurnal fluctuations were only $4.6^{\circ}C$ under 47 and 73% shade. This caused nighttime soil temperatures under 47% shade to average $4.7^{\circ}C$ higher than corresponding temperatures in the unshaded plots. A well-documented effect of shade is a reduced maximum and an

increased minimum soil temperature at any depth (Monteith, 1973).

These results indicate that certain crops such as 'Parris Island Cos' lettuce, 'Waianae Strain' green mustard cabbage, and the bunching onions, have no potential for yield improvement by shading, while the yields of others increase significantly with light shading during certain seasons. Yields of 'Green Mignonette', 'Salinas', and 'Amaral 400' lettuce and 'Tastie Hybrid' head cabbage were increased with shading during Spring 88. The data suggest that the reduction of water stress by shading during this season was the reason for the observed yield increases in these crops, although the evidence is inconclusive.

In the case of 'WR-55 Days' Chinese cabbage, yields were increased by shading during Fall 87 but not during Spring 88. Mean maximum air temperatures during Fall 87 were $33.7^{o}C$ compared to $30.0^{o}C$ during Spring 88, for the time the Chinese cabbage was in the field. Mean minimum air temperatures during both seasons were very similar. Chinese cabbage has been reported to perform poorly when grown during the hot season in tropical lowlands (Sajjapongse and Roan, 1983). It is possible that the temperature reductions caused by shading in the fall were necessary for optimizing yields of 'WR-55 Days'.

Thus, raising certain cultivars of lettuce, Chinese cabbage, and head cabbage under 30 to 47% shade in high insolation areas could improve yields by reducing water stress and air and soil temperature stresses. Because maximum photosynthetic rates were attained at PPFs less than full sunlight for the majority of the crops examined, light shade would still provide enough radiant energy for maximum Pn. More work needs to be carried out with these crops during several different seasons of the year, however, to better understand why shading is beneficial.

CHAPTER V

SUMMARY

This study was undertaken to evaluate the effects of
five different artificially produced shade levels on the
productivity of twelve tropically important vegetable
crops. Four experiments were carried out from the summer
of 1986 to the summer of 1988, at the Waimanalo
Agricultural Research Station, Oahu, Hawaii. Five shade
levels (0, 30, 47, 63, and, 73% shade) were produced by
constructing simple structures of shade cloth supported by
wooden poles. In the first two experiments, 'Waimanalo
Long' eggplant, 'Kahala' soybean, 'Jumbo Virginia' peanut,
'Waimanalo Red' sweet potato, and 'Green Mignonette'
("Manoa") lettuce were planted in three replications.

Based on the beneficial effects of shade on Manoa
lettuce in the first two experiments, a second set of
experiments was devised to investigate the effects of shade
on a wider range of leafy vegetable crops. In these
experiments, four lettuce cultivars, 'Green Mignonette',
'Salinas', 'Parris Island Cos', and 'Amaral 400', as well
as 'WR-55 Days' Chinese cabbage, 'Waianae Strain' green
mustard cabbage, 'Tastie Hybrid' head cabbage, and an
unnamed local selection of bunching onions were planted
under the same five shade treatments as in the previous

experiments. Because of high variability, replications were expanded from three to five.

There were four primary objectives in these studies, namely, to determine the effects of shading on leaf morphology, stages of development, photosynthetic response, and yields of the twelve crops in question. For these reasons single leaf area, single leaf dry weight, stages of development and physiological maturity, photosynthetic rates, and appropriate yield parameters for each crop were evaluated and environmental data collected for both experiments. Each objective is discussed briefly below.

Objective 1. Leaf morphology as influenced by shading.

Shading altered index leaf dry weight and leaf area in all twelve crops, but differently in different crops. Specific leaf area (index leaf area/index leaf dry weight - SLA) of eggplant, soybean, 'Green Mignonette' and 'Amaral 400' lettuce, Chinese cabbage, green mustard cabbage, head cabbage, and bunching onions increased as percent shade increased. This was due to a reduction of index leaf dry weights by shading, while index leaf areas were maintained. This is a common morphological adaptation to shade, because broad, thin leaves increase the light interception possible per unit of structural biomass (Boardman, 1977). Peanut

index leaf area and dry weight were both significantly
reduced by shading, resulting in a SLA which did not
respond to shade. The specific leaf area of sweet potato,
'Salinas' lettuce, and 'Parris Island Cos' lettuce was also
unaffected by shade, but for different reasons. In these
crops, a reduction in photosynthetic photon flux up to the
highest shade level tested had no effect on either leaf
area or dry weight.

Objective 2. Effects of reduced photosynthetically active
radiation on stages of development and physiological
maturity.

Stages of development and physiological maturity of
the majority of crops examined were not influenced by
shading. Soybean and all of the leafy vegetable crops
(i.e. 'Green Mignonette' lettuce in the first experiment
and all of the crops in the second experiment) were not
affected by reduced PAR, with harvest maturity occurring
simultaneously in each shade level. Eggplant, peanut, and
sweet potato developmental stages (e.g. anthesis, time to
bulking), however, were delayed by shading, with darker
shade causing longer delays. These delays resulted in
corresponding delays in harvest maturity, or in the case of
sweet potato, production of smaller and fewer roots
compared to plants grown under higher light intensities.

Objective 3. Photosynthetic rates as influenced by shading.

Net carbon assimilation rates of eggplant, soybean, peanut, and sweet potato increased linearly up to the highest PPF observed with full sunlight (approximately 2200 $\mu mol \cdot s^{-1} \cdot m^{-2}$), with maximum photosynthetic rates ranging from 18 to 24 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ in full-sun. Net photosynthesis of the leafy vegetable crops did not respond in an increasing linear manner to increasing levels of PPF. All of these crops except bunching onions attained maximum photosynthetic rates well below 2200 $\mu mol \cdot s^{-1} \cdot m^{-2}$, at two-thirds to three-fourths of full sunlight. The maximum photosynthetic rates of these leafy crops were lower than those of eggplant, soybean, peanut, and sweet potato, ranging from 9 to 14 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$. Thus, these crops were still able to photosynthesize at maximum rates even when PPF received was reduced by 30%.

'Green Mignonette' lettuce exhibited maximum net photosynthesis at two-thirds of full sunlight during Spring 87, but not during Spring 88. During this second experiment 'Green Mignonette' net photosynthesis increased linearly up to the highest PPF levels tested, unlike the other leafy crops, including 'Green Mignonette' lettuce during the first experiment. There is no obvious explanation for this linear response of Pn of 'Green Mignonette' during Spring 88.

Bunching onions did not respond to changes in the amount of PPF received over the entire range tested. Photosynthesis data were very scattered from -10 (net respiration) to 20 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$. This unresponsiveness to shade most probably is due to the midday closure of stomata exhibited by onion (Heath, 1969). This fact should be taken into account in subsequent photosynthesis studies with onions, and the time when measurements are taken be adjusted accordingly.

Objective 4. Influence of total photosynthetically active radiation received on yield.

Eggplant, soybean, peanut, sweet potato, and green mustard cabbage yields decreased with decreasing amount of total PAR received in both seasons. A linear decrease in yields with increasing shade level was also observed for 'Salinas' lettuce, 'Amaral 400' lettuce, head cabbage, and bunching onions during Fall 1987 and for 'WR-55 Days' Chinese cabbage during Spring 1988. Eggplant fruit number was decreased by shading due to reduced fruit set, while fruit size was maintained regardless of shade. Total seed weights of soybean and seed plus pod weights of peanut were reduced with shading. In the case of sweet potato, both mean single root weight and number of roots were reduced

with reduced total PAR received. Shading caused a reduction of single head weights in the case of green mustard cabbage, 'Salinas' and 'Amaral 400' lettuce, head cabbage, and reduced total bunch weights of onion.

'Parris Island Cos' lettuce yields during both seasons and bunching onion yields during Spring 1988 did not respond to any amount of shading. In the case of the cos lettuce the apparent unresponsiveness to shading was due to a large amount of variability within treatments.

Yields of several of the leafy crops grown in "light" (30 to 47%) shade were similar to or higher than yields from the full-sun plots during certain seasons. 'Green Mignonette' lettuce yields in all plantings, 'Salinas' and 'Amaral 400' lettuce and head cabbage yields in Spring 1988, and Chinese cabbage yields in Fall 1987 grown under light shade were similar to yields from no-shade plots or increased by shade.

Evapotranspiration and air and soil temperatures are high under full sunlight conditions in tropical and subtropical lowland regions; these factors can affect crop performance (Sajjapongse and Roan, 1983; Glenn, 1984; Smith et al., 1984). These environmental stresses were somewhat mitigated by shade during certain seasons, and this change in microclimate apparently was enough to cause a significant positive yield response in certain crops. For those crops exhibiting improved yields with shading, light

shade did not reduce the amount of PPF received to negatively affect maximum photosynthetic rates. A seasonal variation in yield responses to shade would be expected, with shading not resulting in increased yields when moisture and/or temperature stresses were not great. In the case of Manoa lettuce, for example, 30 to 47% shading did not reduce yields in any of the trials, although in Spring 1987, when temperatures were cooler compared to Fall 1986, yields were not increased by shade. This indicates that this lettuce cultivar could be successfully grown under light shade in a permanently lightly shaded environment. During seasons of high temperatures or high evaporation rates, shading could bring about yield increases, while during low stress seasons, shading would not cause reduced yields in this cultivar.

This study indicates that a number of the crops examined have the potential for yielding well in a multiple crop situation. Those leafy vegetable crops whose yields were increased when grown under artificial shade would probably exhibit similar yield responses in naturally shaded environments. A study using sweet potato demonstrated this relationship between artificial and natural shade. Martin (1983) carried out shading studies with a large number of sweet potato lines which were selected for shade tolerance under artificial shade. Those

lines which, under shade, yielded as well as or better than when grown in full sunlight, were then planted under naturally shaded conditions (produced by mango trees). Similar results were obtained in both studies. It was indicated, however, that only certain sweet potato lines actually exhibited shade tolerance, a fact which has been demonstrated in other horticultural crops, as well. For example, studies carried out with six tomato selections relay cropped with corn demonstrated that only some of the tomato lines produced marketable yields equal to or greater than monocrop yields (Villareal and Lai, 1981).

Of the twelve cultivars examined in this study, 'Green Mignonette' lettuce, 'Amaral 400' lettuce, 'Salinas' lettuce, 'WR-55 Days' Chinese cabbage, and 'Tastie Hybrid' head cabbage probably have the most potential for being grown successfully in multiple cropping systems. The next step would be to grow these five crops in a multicropped situation in order to investigate their performance in a naturally shaded environment in close association with other crops. Such a study would provide a more accurate indication of their potential as intercrops.

It should also be pointed out that some of the other crops examined, e.g. 'Waimanalo Red' sweet potato, 'Waianae Strain' green mustard cabbage, and bunching onions, whose yields were not increased by shading, had only somewhat reduced yields under light shade compared to full-sun plots

and could still be considered for use in multiple cropping. In situations where the land between the principal crop (e.g. in perennial tree plantings) is unused, one of these crops could be planted for additional income. Although the yields of the annual crop would be reduced compared to its yields in full sunlight, additional income would be provided to the grower from otherwise idle land. Again, field trials of such a situation would be the next step after this preliminary study to further investigate the multiple cropping potential of these cultivars.

The implications of this study are more far-reaching than just establishing the consequences of shading in an intercrop situation. Even in high insolation regions where multiple cropping is not desired, growers may still consider shading crops which could benefit from the practice through the use of artificial shade structures. Shading can also help lower the costs of irrigation, an important consideration in many areas. According to Ekern (1983) a linear relationship exists between sunlight incidence and rate of evaporation. Based on evaporimeter results in open-sun plots and in 73% shade (39% reduction in water loss compared to full-sun), shading by 47% would result in a 25% reduction in water loss due to evaporation.

Discussing these results in economic terms, shading of certain crops does appear to have economic feasibility

under Hawaiian conditions. Manoa lettuce has a farm gate value of about $0.45·lb^{-1} in Hawaii (K. Takeda, personal communication). A 40% increase in yields due to shade (based on experimental results) above the 12,500 lb·acre^{-1} yearly Oahu average would amount to an income increase of $2250·acre^{-1}. A 25% reduction in water usage would equal a savings of about $50·acre^{-1} for a 60 day growing period (based on $0.84·1000 gal^{-1} for first 13,000 gal and $0.69·1000 gal^{-1} for the remainder). Thus, shading could increase incomes for Manoa lettuce by $2300 per acre per crop. If yield increases from shading occurred with half of the six crops typically grown by Manoa lettuce growers on Oahu per year, gross revenues could be increased $6900/year. Similar calculations for 'Amaral 400' lettuce, 'Salinas' lettuce, 'WR-55 Days' Chinese cabbage, and 'Tastie Hybrid' head cabbage result in per acre increases of incomes of $1150, $655, $627, and $1000, respectively. Taking into consideration the costs of shade structure construction, and the fact that only 'Green Mignonette' lettuce yields were not reduced by shading during any season, it is probably only economically feasible to grow this crop under shade on Oahu. More work needs to be carried out with all of these leafy crops, as well as with others at various seasons, in order to better establish which crops would be most benefitted by shade during which seasons.

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