THE DYNAMIC ROOT FLOATING HYDROPONIC TECHNIQUE: YEAR-ROUND PRODUCTION OF VEGETABLES IN ROC ON TAIWAN

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ABSTRACT

The paper discusses the feasibility of using hydroponic techniques in the year-round production of high-quality vegetables in ROC on Taiwan. In order to increase the vegetable supply during the summer, with its unpredicable weather conditions, and to meet the requirements for hygienic vegetables, the dynamic root floating (DRF) hydroponic technique was developed at the Taichung District Agricultural Improvement Station in 1986. The DRF technique is based on the use of a low typhoon-proof greenhouse with a framework of piping, a ridged culture bed, concave panels, an aspirator, a nutrient level adjuster, a nutrient exchange box and a nutrient concentration controller. Over the hot summer season, the DRF technique reduced the build-up of heat in the greenhouse, and induced plants to develop an aeroroot system to overcome the shortage of dissolved oxygen in the nutrient solution. There are now more than 19 ha of DRF hydroponic vegetable factories run by 150 growers in Taiwan, and another 0.6 ha in various parts of Thailand, Malaysia and Singapore. This paper mainly focusses on how the DRF technique makes possible the successful year-round production of leafy vegetables in tropical and subtropical areas.

INTRODUCTION

Taiwan is an island located in the tropical and subtropical regions, with the Tropic of Cancer running across the center of the island. The Central Mountain Range, running from north to south, divides the island into the eastern and western regions, and two-thirds of the island is thus sloping or hilly land. There are marked seasonal changes in temperature, with an average minimum of 9.4°C in January and a maximum of 34.2°C in July. The minimum precipitation is 25.6 mm (January) and the maximum 362.1 mm (June). Typhoons and heavy rainfall followed by flooding often affect Taiwan, destroying protected agricultural facilities. Thus, typhoons, heavy rainfall and high temperatures are major constraints to growing vegetables during the summer. In consequence, the supply of vegetables during this season is unpredicable, and market prices are high in summer and fluctuate throughout the year (TAPMC 1988). Furthermore, with growing prosperity in Taiwan, consumers are demanding hygienic, high quality vegetables free of pesticides, while growers, faced with frequent pest outbreaks in the hot, humid climate, have been tending to use too much pesticide for the past thirty years. In order to solve these problems, the Taichung District Agricultural Improvement Station (DAIS) initiated a research program in 1983 on greenhouse crop cultivation, to develop techniques for promoting and stabilizing the production of summer vegetables. However, the weather is too hot to grow vegetables in a nethouse or plastic film house. Moreover, continuous monocropping using similar species of vegetables causes salts to accumulate in the surface soil, while severe pest infestations do great damage to greenhouse vegetable crops (Kuo 1987, Kuo *et al.* 1989). In addition, the frequent destruction of greenhouse frameworks and crops by typhoons and storms meant that farmers could not rely on getting any return for their investment. In a series of experiments on hydroponic techniques carried out at the Taichung DAIS, the results showed that the high temperatures inside the greenhouse, together with the low level of dissolved oxygen in the nutrient solution, meant that the yield of vegetables was very low in conventional soilless culture during the summer (Kao 1987). An economic and practical design for a hydroponic system in Taiwan must thus consider, not only the hydroponic technique itself, but also the greenhouse structure, in order to overcome these difficulties (Kao 1990). Finally, we developed a novel system called the dynamic root floating (DRF) hydroponic system, which proved ideal for growing various kinds of vegetables, not only during the hot summer season but during the rest of the year as well (Kao 1987, 1988, 1990; Kao *et al.* 1989).

The nutrient film technique (NFT) was developed by Dr. Allen Cooper in England in 1970, to increase the year-round production of greenhouse crops in England. It has since been widely adopted in western Europe (Cooper 1988, Douglas 1976, Resh 1987). The deep flow technique (DFT) is a modified hydroponic culture method, which has been developed in Japan since 1973 specifically for the year-round production of Japanese honewort (*Cryptotaenia japonica* Hassk.) (Ikeda 1984, 1985; Suzuki *et al*. 1984, Yamasaki 1986). The following paper presents the DRF hydroponic technique, and compares it with the NFT and DFT systems.

MATERIALS AND METHODS

In order to evaluate the DRF hydroponic system, a series of experiments has been conducted at Taichung DAIS since 1987. Comparisons were made between the DRF and two other types of hydroponic system i.e. DFT and NFT. All hydroponic systems were installed according to the original design (Cooper 1988, Douglas 1976, Resh 1987, Ikeda 1984, 1985; Suzuki *et al*. 1984) with a nutrient flow path 15 m long in the DFT and NFT systems, and 2 m long in the DRF. During these experiments, measurements were made of the pH, electric conductivity (EC), the temperature and dissolved oxygen concentration of the nutrient solution, vegetable fresh weight, root morphology and root activity. Greenhouse microclimatic conditions (including greenhouse (inside) temperature, ambient temperature, relative humidity and carbon dioxide concentrations) were also recorded. Portable equipment such as a DO meter (Suntex model SD-70), a temperature meter (Suntex model ST-1), a relative humidity meter (Hanna HI-8564), a pH meter (Suntex SP-12) and an EC meter (Suntex SE-17), were used in the experiments. The carbon dioxide concentration of the greenhouse was detected by infra-red gas analyzer (Beckman 8321-01-041). The root respiration rate, as a measure of root activity, was estimated on the basis of the level of carbon dioxide according to the in/reflux method (Kao 1987). Details of the system design for the DRF hydroponic technology are as follows:

Low Greenhouse with Piping Framework

The DRF hydroponic system comprised a ridged culture bed, a concave panel, an aspirator, a nutrient level adjuster, a nutrient exchange box and a nutrient concentration controller, all of which were housed in a low, typhoon-proof greenhouse (Fig. 1). The framework of the greenhouse was made of galvanized tubular iron piping 0.5" F and 0.75" F. The standard width of the house was 2.13 m, with a height of 2.1 m. The length of the house could be extended indefinitely, depending on the vegetable supply and the grower’s production capacity. A dew-resistant transparent PVC plastic film 0.15-0.20 mm thick was lain on top of the greenhouse as a rainproof cover, while the sides were covered with a white polythene plastic net (24 mesh) to keep insects out. When the inside temperature was higher than 30°C, a black polythene plastic net (25-40% shading capacity) was hung 30 cm above the plastic house to reduce the build-up of heat in the greenhouse.

Ridged Culture Bed

The wave shaped culture unit was constructed from polystyrene board, and was 2.01 m wide and 90.1 cm long, with a height of 15 cm at the sides. The nutrient bed was lined, to insulate it from the inside temperature of the greenhouse, and was then given a second inner lining of a black polythene sheet 0.2 mm thick to render it waterproof. Each culture bed contained eight ridges (and nine gullies) (Fig. 2).

Concave Panel

The panel shown in Fig. 2 was also made from polystyrene board, and measured 90.1 cm (L) x 88.0 cm (W) x 4.0 cm (T). Each panel had 80 circular holes an equal distance apart. The panel was flat on one side and had a 1.0 cm deep concave depression on the other side, around each hole, to give the 48.1 (8.3 x 5.8 x 1.0) cubic centimeter of air space used for aeroroot induction.

Nutrient Level Adjuster and Aspirator

Each unit of the DRF hydroponic greenhouse had a nutrient exchange box, which consisted of a nutrient level adjuster and a nutrient outlet plug

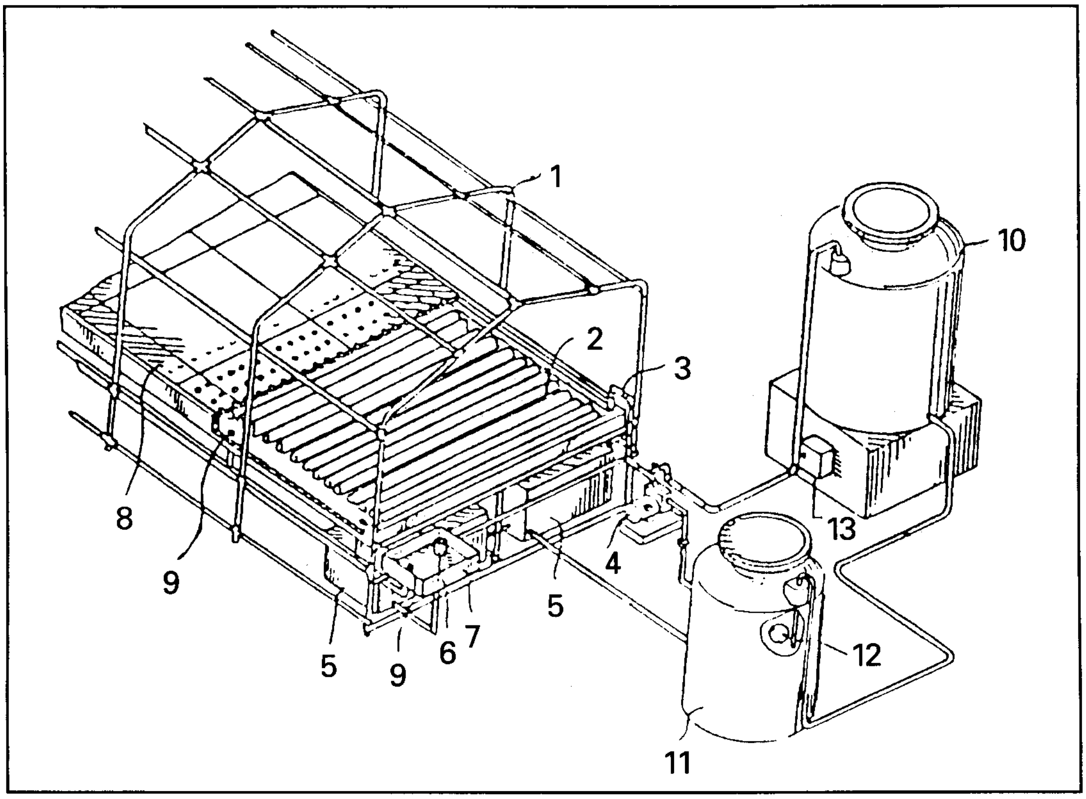

Fig. 1. The components of the DRF hydroponic technology.

1. Pipe house, 2. Culture bed, 3. Aspirator, 4. Pump, 5. Reservoir, 6. Nutrient level adjuster, 7. Nutrient exchange box, 8. Panel, 9. Nutrient outlet plug, 10. Upper nutrient tank, 11. Lower nutrient tank, 12. Floating switch, 13. Nutrient controller box

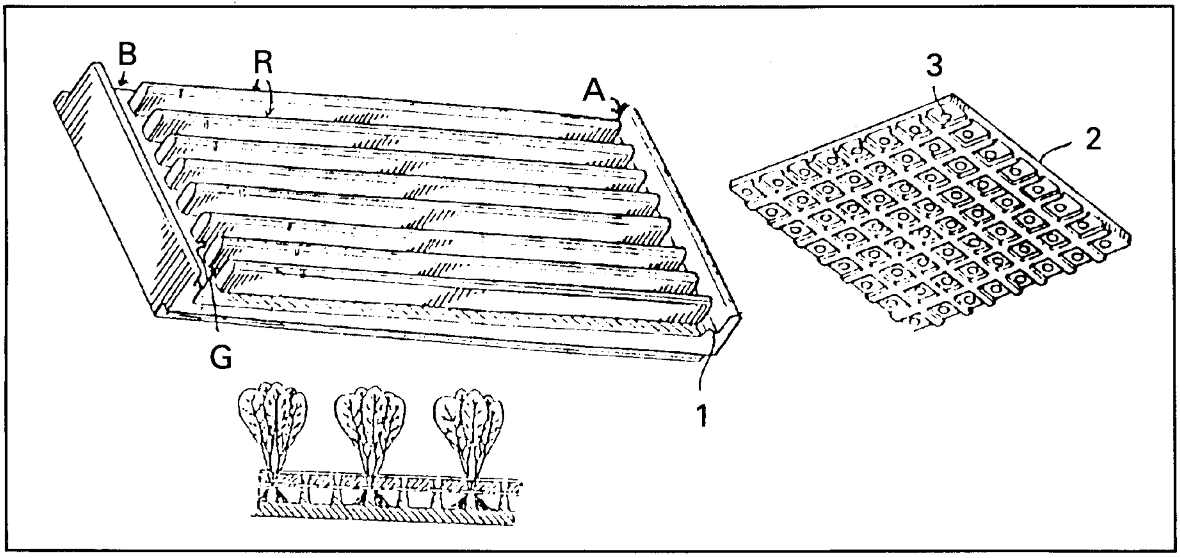

Fig. 2. The appearance of the ridged culture bed and concave panel.

1: Culture bed, 2: Panel, 3: Air space inside concave hole. A: Nutrient inlet and B: Outlet gutter, R: Ridge of channel, G: Gully

(Fig. 3). Nutrient outlet plugs were set 3.6 m apart in the bottom gutter of the culture bed, connected by a 1" F PVC pipe to the nutrient exchange box. The nutrient level adjuster was made from 5" F ABS plastic tube containing a double set of inner rings (Fig. 3). The outer ring was 8 cm high, and two 0.5" F holes were cut at the bottom of the outer ring to allow nutrient solution flowing through and over the inner ring to run back into the reservoir. The inner ring was 3" F in diameter and 8 cm high. This inner ring contained four linked rings, 3, 2, 2 and 1 cm high, respectively. The height of this set of inner rings could be adjusted from 8 cm to 0 cm, according to the state of vegetable growth.

In the east side of the culture bed was a 0.5 cm F PVC plastic nutrient supply pipe running into the main gutter. The nutrient supply tube had a tiny hole where it ran through each gully. The aspirator was connected to the nutrient supply pipe at one end, and to the pump at the other end. The aspirator was designed to have a four-bladed propeller inside the tube, while two holes 0.1 cm in diameter were cut opposite each other so that the nutrient solution would absorb more air as it flowed through.

Nutrient Circulation System

The frequency with which the nutrient solution was pumped through the DRF hydroponic system was controlled by an automatic timer insulated within the nutrient controller box (see Fig. 1 and Fig. 3). An automatic pumping cycle was set up, with a flow of 6/24 minutes on/off during the daytime, and 6/174 minutes on/off at night. The nutrient in the DRF system was recirculated. It was first enriched by solution pumped from the reservoir, then passed through the aspirator and the nutrient supply pipe to spray into each gully, collecting in the bottom gutter to run into the nutrient exchange box and back into the reservoir again. In Fig. 2 and Fig. 3 the letters A and B show the inlet and outlet gutter respectively of the nutrient flow path, which was no more 2 m long. A constant concentration of nutrients in the solution was maintained automatically by

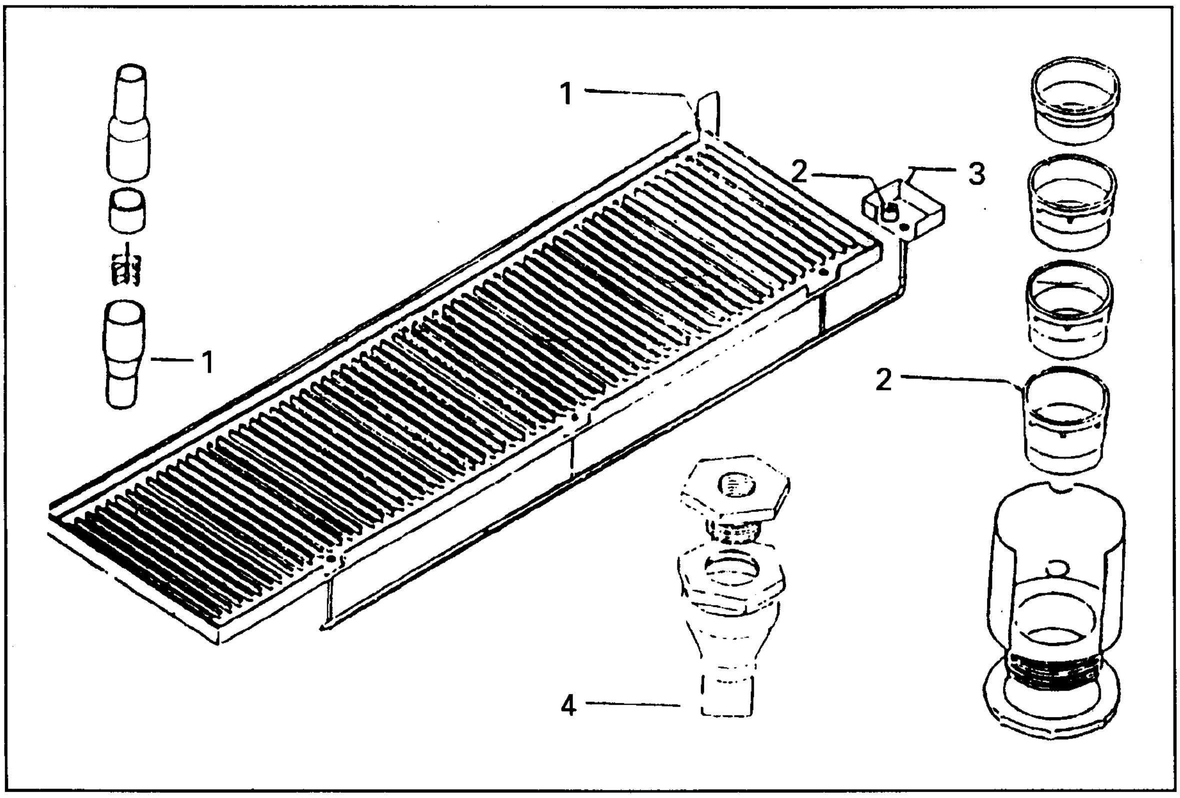

Fig. 3. Components of the DRF hydroponic nutrient flow system.

1. Aspirator, 2. Nutrient level adjuster, 3. Nutrient exchange box, 4. Nutrient outlet plug

an insulated floating switch in the lower nutrient tank (Fig. 1). When 3% of the total amount of nutrient solution in the DRF hydroponic system had been used, the floating switch automatically turned on to allow twice as much concentrated nutrient solution to run from the upper nutrient tank into the reservoir. Since the lower nutrient tank was connected with the reservoir, a constant level of nutrient solution could thus be maintained.

Factorized Design

The standard model for a DRF hydroponic vegetable factory was designed as a 24-greenhouse complex. The layout of the DRF hydroponic vegetable factory in an area of 43.6 x 19.78 m^2 is shown in Fig. 4. The growth period of Chinese leafy vegetables, for instance, was 24 days in the DRF hydroponic system. The routine work of the grower consisted only of the transplanting and harvesting operations in two of the 24 individual houses at any one time, while growing crops were maintained by an automatic hydroponic system in the other 22 greenhouses.

Cropping Patterns

There were two cropping patterns in the course of the year (Table 1). The first cropping pattern was from April until October 10th (a national holiday in China), which covered the hot summer period. The second cropping pattern was from October 10th to the following March. Traditional Chinese leafy vegetables such as pak-choi (*Brassica Chinese* L.), Chinese kale (*Brassica oleracea* L.), leafy mustard (*Brassica juncea* L.), edible amaranth (*Amaranthus tricolor* L.), water convolvulus (*Ipomoea aquatica* Forsk), and leafy lettuce eaten as a cooked vegetable (*Lactuca sativa* L.) etc. were suitable crops for the first cropping pattern. Cucumber (*Cucumis sativus* L.), tomato (*Lycopersicon lycopersicum* L.), muskmelon (*Cucumis melo* L.), celery (*Apium, Graveolens* L.), butterhead or crisp lettuce for salads (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), and garland chrysanthemum (*Chrysanthemum coronarium* L.) were selected for the second cropping pattern. Water convolvulus and Chinese leek (*Allium tuberosum* Rottl, ex. K.) were suitable for all-year-round ratoon growth.

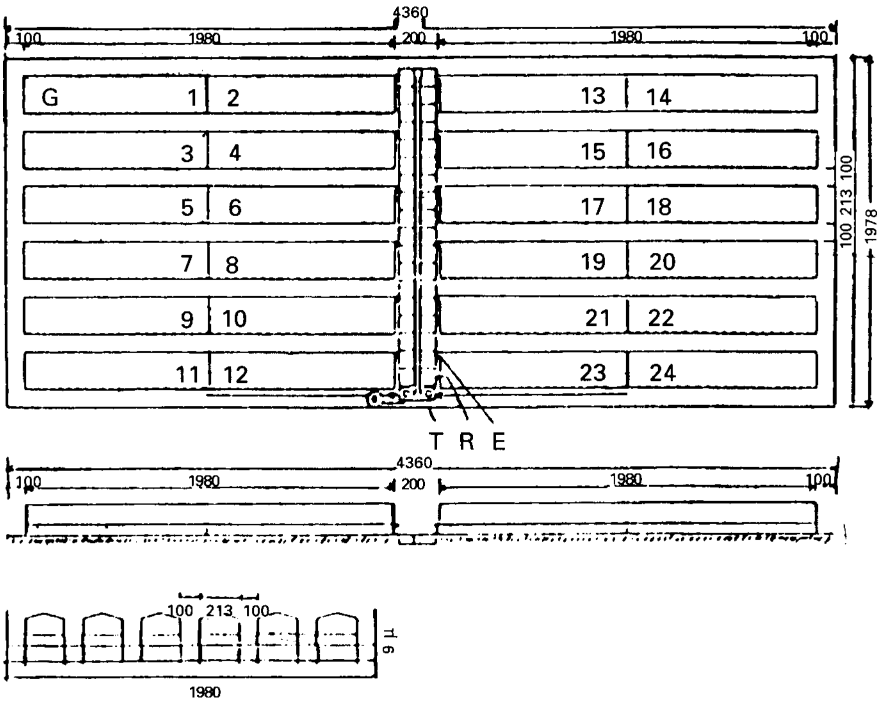

Fig. 4. Layout of the standard DRF hydroponic vegetable factory, with 24 greenhouses on a piping framework in 43.6 x 19.78 m^2.

G: Greenhouse, T: Nutrient tank, R: Reservoir, E: Nutrient exchange box

Cultural Practices

Vegetable seedlings were grown in a polyfoam (polyurethane sponge) block for several days, the length of time depending on the species of vegetable grown. When the root length of the seedlings reached 3-5 cm or the primary leaf was well developed, the seedlings were transplanted into precut holes in the panels. The root system of the seedlings had to be immersed in the nutrient solution, so that the plants could grow on the ridges of the culture bed (Fig. 2). The planting density in each panel varied from 80 to 8 plants, according to the type of vegetable grown. Tall fruit vegetables were supported by a nylon net tied to the overhead frame of the house. Table 2 shows the number of days to germination, to the seedling stage, from transplanting to harvest, and planting density, for various vegetable species.

Nutrient Solution

The standard nutrient formula used in the DRF system could be used to grow all kinds of crops, but an increase in macroelement concentration was needed for some cropping seasons and vegetable species (Table 3 and Table 4) (Kao 1990). The concentration of micro-elements was maintained at a constant level.

Adjustment of Nutrients

The nutrient concentration is maintained at a constant level in DRF hydroponics according to the following simulation model.

$$EC_f = \frac{(W-X) \times EC_d}{W} + \frac{X}{W} \times EC_a$$

EC_f: Final concentration in hydroponic system (mmho/cm)

EC_d: Nutrient concentration when measured (mmho/cm)

EC_a: Additional nutrient concentration (mmho/cm)

W: Total nutrients in whole hydroponic system (1)

X: Total nutrients lost from whole hydroponic system (1)

On the basis of this simulation model, nutrient solution stocked in the upper nutrient tank was at a double concentration, and automatically passed through the floating switch to enter the lower nutrient tank, simultaneously running to fill the reservoir up to the set level. The reservoir and the lower tank were designed to connect together, with the floating switch in the lower nutrient tank. Thus, the floating switch began functioning when a 3% loss of the total nutrient solution occurred in the reservoir.

RESULTS: MICROCLIMATIC CONDITIONS

The low greenhouses on a piping framework used in the DRF hydroponic system could

Table 1. Vegetable cropping patterns in a DRF hydroponic system

Cropping Pattern	Cultivation Calendar	
	April May June July Aug. Sept.	Oct. Nov. Dec. Jan. Feb. Mar.
	LEAFY VEGETABLES	
I	Pak-choi, Chinese kale, Leafy lettuce, Edible amaranth, Leafy mustard, Water convolvulus, Chinese leek	Garland chrysanthemum, Japanese pak-choi, Celery, Spinach, Salad lettuce, Crisp lettuce, Head lettuce
II	LEAFY VEGETABLES SAME AS CROPPING PATTERN I	FRUIT VEGETABLES Tomato, Cucumber, Muskmelon

Table 2. Days for growth and developmental stage of various vegetable species

Vegetable Species	Growth Stage			Planting Density
	Germination (days)	Seedling (days)	Harvest (days)	(plants/panel)
Pak-choi	1-2	7-10	24	80
Chinese kale	2-3	10-16	30	80
Leaf mustard	1-2	7-14	24	80
Edible amaranth	2-3	10-16	24	80
Water convolvulus	2-3	7-14	24	80
Spinach	3-4	10-16	24	80
Garland chrysanthemum	3-4	10-16	24	80
Leafy lettuce	1-3	10-16	24	80
Butterhead lettuce	3-4	16-20	35	8
Crisp lettuce	3-4	16-20	45	8
Celery	7-10	15-20	40	40
Tomato	5-7	20-25	90	9
Cucumber	3-5	15-20	90	4
Muskmelon	3-5	15-20	80	2
Chinese leek	30-40	20-30	20	80

Table 3. Standard concentration of nutrients in nutrient solutions

Macroelement	(me/liter)	Microelement	(ppm)
NO_3-N	6.0	Fe EDTA	2.5
NH_4-N	0.5	B	0.2
PO_4-P	3.0	Mn	0.2
SO_4-S	1.5	Zn	0.01
K	4.0	Cu	0.01
Mg	2.0	Mo	0.01
Ca	4.0		
EC (mmho/cm, 25°C)		1.0	
PH		6.0	

Table 4. Nutrient concentration used for growing hydroponic vegetables

Cropping Pattern	Standard concentration (S)	EC (mmho/cm) 25°C	pH
I	1.5-2.0 S	1.5-2.0	5.5-6.0
II	2.0-2.5 S	2.0-2.5	6.0-6.5

maintain a constant inside temperature if natural ventilation was used. Since a black net giving 25-40% shade was hung 30 cm above the roof of the pipe house, the inside temperature was only 1.2°C-3.9°C higher than the ambient temperature. This can be compared to the greenhouse effect which gives a 3.4°C-5.9°C temperature increase in the traditional tunnel house. In addition, the ventilation in tunnel houses is so poor that the relative humidity and the concentration of carbon dioxide fall (see Table 5). In a house made of piping, in other words, no electrically run cooling facility is needed to reduce the build-up of heat.

NUTRIENT TEMPERATURE

The nutrient temperature in the DRF hydroponic system was maintained at a constant level. The culture bed made from polystyrene board used in the DRF system could keep the temperature of the nutrient solution (NT) more stable than one made from asbestos sheet. Table 6 illustrates the difference in NT between the ridged culture beds made of polystyrene, and those made of asbestos sheets. There was a difference of 2.10°C between the two kinds of culture bed when the inside air temperature was 7.0°C, but a difference of 4.4°C when the inside air temperature reached 38.4°C.

DEPTH OF NUTRIENT SOLUTION

The NT could be adjusted either by increasing the pumping volume or by prolonging the circulation period. However, if the depth of the nutrient solution in the culture bed was not maintained at more than 3-4 cm, the vegetable yield varied with changes in the greenhouse air temperature (Kao 1987, 1988). The NT variation shown in Fig. 5 indicates that DRF and DFT were better than NFT in limiting temperature differences when the air temperature rose to 37°C, or fell to 25°C. The nutrient circulation period in the experiment for the DRF and DFT techniques was 6/24 minutes on/off, compared with the continuous flow in the NFT method. The only reason why the NT in NFT was higher than in DRF and DFT was because the nutrient solution in NFT was only 1-2 cm deep, compared to the depth of 3-8 cm in the other systems.

DISSOLVED OXYGEN

The concentration of dissolved oxygen (DO) in the nutrient solution decreases with an increase in the ambient temperature (Douglas 1976, Resh 1987). This results in an undesirable fall in the respiration rate of the hydroponic roots, due to the shortage of DO in high-temperature nutrient solution (Kao 1988). The dissolved oxygen level could be forced upwards by prolonging the nutrient circulation period — i.e. by a non-stop flow in NFT — but the amount of electricity consumed meant that this was of little practical use. The aspirator was a special device used in the DRF hydroponic system to increase the DO in the nutrient solution automatically while the circulation system was operating. The aspirators could oxygenate nutrient solution being pumped at 7.5-8.0 liters/minute, so that the solution was saturated with DO (Kao 1987). Nineteen or twenty aspirators could be operated simultaneously by a 1 HP pump.

The nutrient level adjuster placed in the nutrient exchange box of the DRF hydroponic system was used to increase DO by producing an alternation of 1-2 cm in the depth of the nutrient solution. The height of the outer ring of the nutrient level adjuster was fixed at 8 cm, while that of the inner ring could be adjusted. The variation in DO

Table 5. Microclimatic conditions in two types of greenhouse

Treatment	Room Temperature (°C)		Relative Humidity (%)		Carbon Dioxide (ppm)	
	Tunnel house	Piping house	Tunnel house	Piping house	Tunnel house	Piping house
40% shading	41.6	39.4	59.5	59.9	270-310	325-347
No shade	44.1	42.1	48.6	53.5		

** The ambient temperature was 38.2°C, relative humidity was 58.7% and carbon dioxide concentration was 330-350 ppm at 1130 AM, June 19, 1990.

Table 6. Effect of air temperature inside the greenhouse and different hydroponic culture bed materials on the temperature of the nutrient solution

Inside air temperature (°C)	Temperature of nutrient solution (°C)	
	Ridged culture bed	Asbestos sheet
7.0	10.1	8.0
20.5	16.5	18.2
27.1	21.2	22.9
31.3	24.5	26.9
35.2	27.2	31.2
38.4	30.3	34.7

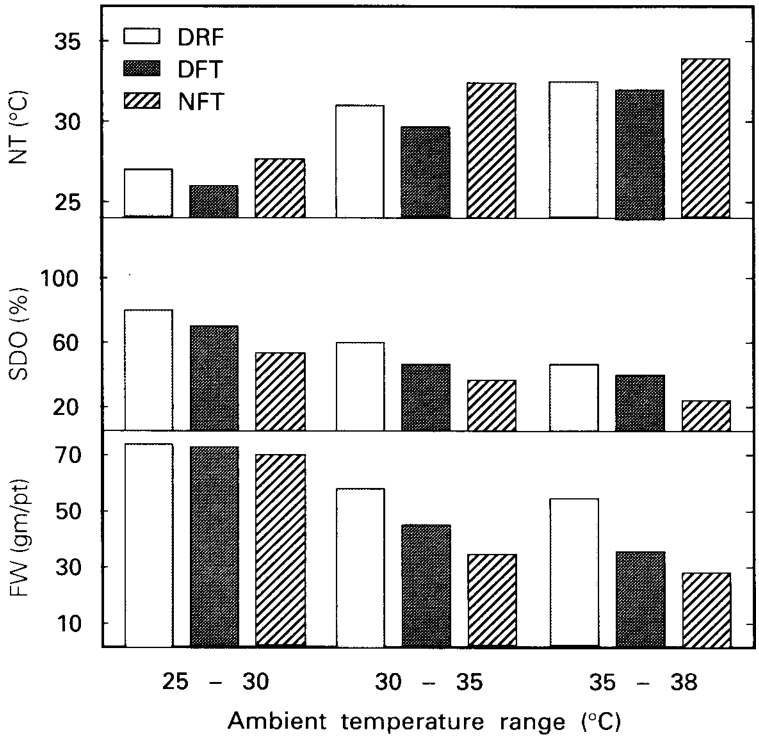

Fig. 5. Changes in nutrient solution temperature, dissolved oxygen and fresh weight of pak-choi in NFT, DFT and DRF hydroponic systems.
SDO: Saturated dissolved oxygen, NT: Nutrient temperature, FW: Fresh weight

shown in Fig. 6 indicates that DO could be increased during the six-minute pumping period in the DRF and DFT systems. However, it would fall to 30% of saturation level 13 minutes after pumping stopped in DFT, and 24 minutes afterwards in DRF. It was also found in DFT that the depth of the nutrient solution fell rapidly to its original level 10 minutes after pumping stopped, while this was delayed to 24 minutes in DRF. Thus, the function of the nutrient level adjuster was to move the level of nutrient solution up and down in the culture bed. In NFT, since the flow of the nutrient solution was continuous, DO could be kept at 45-50% of saturation level. However, if the room temperature reached 37°C, the DO in NFT fell to 30-40% of saturation level, reducing the growth vigor of vegetable crops.

AEROROOTS

The function of the concave panel designed for the DRF hydroponic system is to induce the growth of 'aeroroots' which develop from the immersed root mat. Previous reports have indicated that, when the roots of hydroponically grown plants suffer from high NT (e.g. over 30°C), they become brownish and show little activity (Kao 1987). It was also found that if the air space between the panel and the nutrient solution could be gradually increased to 3-4 cm, the immersed roots would divide into two sections i.e. the aeroroots and the nutriroots. When the aeroroot section was surrounded by wet air at 100% RH, groups of root hair-like white roots ('aeroroots') would be induced after 3-5 days (Fig. 6). The aeroroots formed a V shape as they reached the ridge of the culture bed. As the level of the nutrient solution in the gully fell, aeroroots were produced from the upper surface of the root mat (Fig. 7). A similar phenomenon was described by Dr. Cooper in NFT, and by Dr. Yamasaki in his floating hydroponics system. In NFT production, the plants are grown bare-rooted in long, narrow channels, down which flows a very shallow stream of recirculated nutrient solution (Cooper 1988). In floating hydroponics technology, the nutrient solution runs beneath a floating net, to provide moisture to the upper root mat and induce root growth (Yamasaki 1986). Vegetables grown by DFT have no aeroroots, because there is no air space between the panel and the nutrient solution. Hence, if the DO is not sufficiently high in DFT, the upper root system is forced to extend up onto the panel. The root activity of the two kinds of root systems shown in Table 7 varied according to the temperature of the nutrient solution. The carbon dioxide was measured *in situ* by the reflux method as root activity (RA) at different growth stages (Kao 1987). Fig. 5 shows that DO as well as vegetable fresh weight responded to an increase in temperature. In general, RA was promoted by a fall in the temperature of the nutrient solution, no matter what kind of hydroponic system was used. There was no significant difference in vegetable fresh weight between DRF, DRT and NFT at 25°C. However, poor RA in plants grown by NFT at 35°C resulted in low yields. In DRF, with its increased air space, the RA as well as vegetable fresh weight increased significantly. Aeroroots continued to perform well in DRF even when temperatures

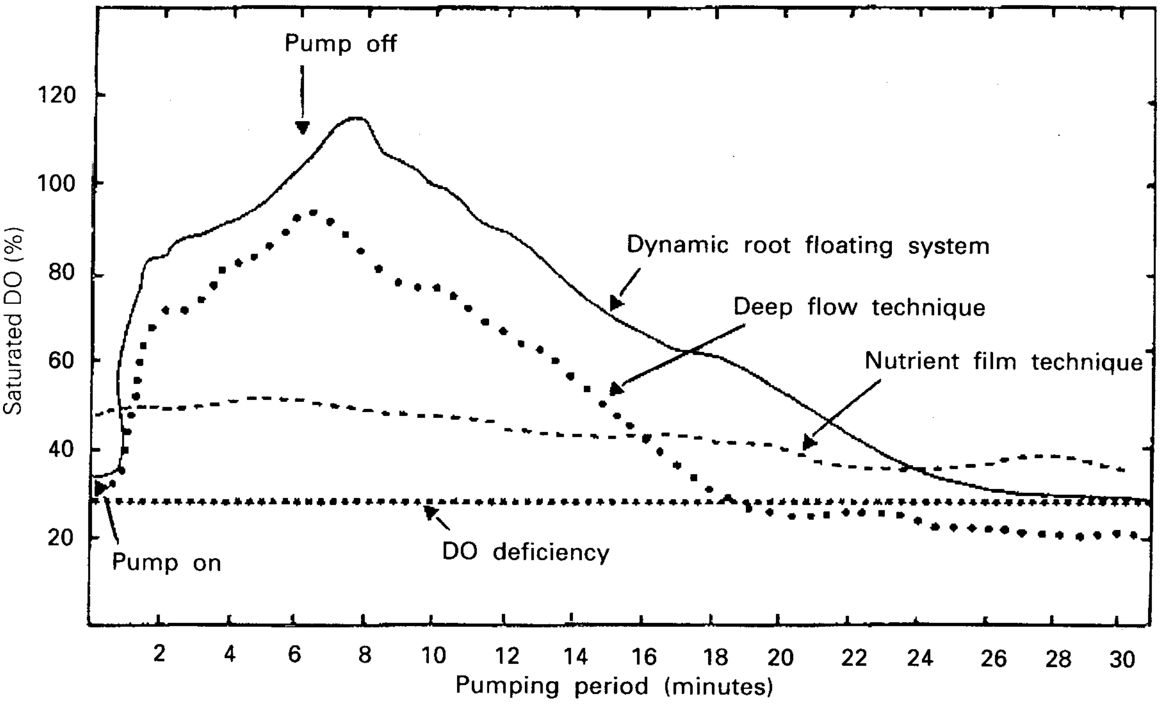

Fig. 6. Variations in the dissolved oxygen content during pumping of nutrient solution in three different hydroponic systems

were higher than 35°C. Additional DO should be added at temperatures higher than 35°C, otherwise yields are poor. Increasing the air space so as to obtain enough aeroroots (bare roots or wet moist roots) at 35°C seems to be the best solution to the problem of producing high fresh vegetable weights with an NFT system.

Automatic Management of Nutrient Solution

Routine management of the nutrient solution in the DRF hydroponic system was controlled according to a simulation model, as mentioned above. We found that if $X/W < 3\%$ and $EC_d/EC_a < 1\%$, then EC_f would tend to become equal to EC_a after additional nutrient solution had been supplied for 24 days (Kao 1990). As shown in Table 8 the observed nutrient solution concentration in hydroponically grown pak-choi was not significantly different to the simulated curve during 24 days of operation. If the nutrient concentration is not adjusted, the nutrient status varies, resulting in lower yield potential. Table 8 shows variations in the nutrient status and fresh weight of pak-choi during a 24-day growing period, during which the pH in the treatment in which conditions were controlled was raised to 7.8 and the EC was reduced to 1.1 mmho/cm if the plants were grown at 17-21°C. At 27-31°C, the pH was kept at 4.9 and the EC at 2.9 mmho/cm. If the pH and EC were not controlled, there was a fresh weight loss of 34-36%.

Productivity

The seasonal yield potential of various vegetable crops grown in a DRF hydroponic system is shown in Table 9. In traditional production, climatic conditions in Taiwan over the winter (cropping pattern II) are much better than during the summer (pattern I) in central and southern Taiwan. Large quantities of cheap leafy vegetables are produced in paddy fields in winter after the second rice crop, reducing the market potential for hydroponic vegetables. In order to solve this problem, it is recommended that half the greenhouse complex in the DRF hydroponic vegetable factory be used to grow fruit vegetables for cropping pattern II, because tomato, cucumber and muskmelon can still fetch good prices in the winter season in Taiwan (TAPMC 1988). Furthermore, the initial harvesting date is one month earlier for hydroponic fruit vegetables than for conventional soil culture, so that growers can get the same return as that earned from leafy vegetables over the summer.

Capital and Running Costs

The capital cost of constructing a DRF hydroponic vegetable factory 19.78 x 43.6 m^2 was US$27,700 (Table 10). The annual gross income was US$35,718.2, and running expenses cost US$26,189.6 (Table 11). Therefore, the net profit earned from managing such a DRF hydroponic vegetable factory was US$9,528.6 per annum. Over four to four and a half years, the producer can recover the whole cost of his investment.

CONCLUSION

The seasonal productivity in a DRF hydroponic vegetable factory is fairly stable. Since microclimatic conditions in the low greenhouse with a piping framework were similar to those in the open field, the temperature of the nutrient solution could be maintained at a constant level to provide good growing conditions for vegetables grown in a DRF hydroponic system. A DRF promotes the development of a V-shaped aeroroot system, because of its use of ridged culture beds, concave panels and a nutrient level adjuster. These devices were designed to maintain an air space of 0-4 cm between the upper surface of the nutrient solution and the lower panel of the culture bed. A sufficient oxygen supply was maintained by periodically changing the level of the nutrient solution by 1-2 cm, with the help of an aspirator and nutrient level adjuster. Providing an ample oxygen supply, and keeping the roots alternatively wet and semi-dry, resulted in high productivity even under high temperature conditions. This is therefore a practical hydroponic system for subtropical and tropical regions. Such a design must be concerned, not only with the ability of natural ventilation and insect-proofing to maintain good conditions inside the greenhouse, but also by the ability of the culture system to promote the development of aeroroots. A DFT system can maintain a more constant temperature in the nutrient solution but is not able to induce aeroroots. These characteristics are reversed in the NFT system. Considering that ambient temperatures in the tropics are generally around 30-35°C, the function of maintaining a constant nutrient temperature might be more important than aeroroot induction. However, the DFT system was deficient in dissolved oxygen, with consequent poor root activity if the temperature of the nutrient solution was higher than 30°C. Therefore, the ability to induce aeroroots is a key point in

Fig. 6. The appearance of aeroroots and nutriroots of pak-choi grown in a DRF hydroponic system. The upper root system which is white in color is the aeroroots, and the lower brown roots are the nutriroots

Fig. 7. V-shaped root system of pak-choi grown on ridged cultaure bed in a DRF hydroponic system. Aeroroots were enriched on

Table 7. Effect of nutrient solution temperature on root activity (respiration rate, mg CO_2/ minute) of pak-choi

Hydroponic system	25°C			35°C		
	Aeroroots	Nutriroots	Total	Aeroroots	Nutriroots	Total
DRF	57.9	26.5	84.4	34.7	22.9	57.6
NFT	63.6	19.4	83.0	13.2	8.7	21.9
DFT	-	46.3	46.3	-	27.6	27.6

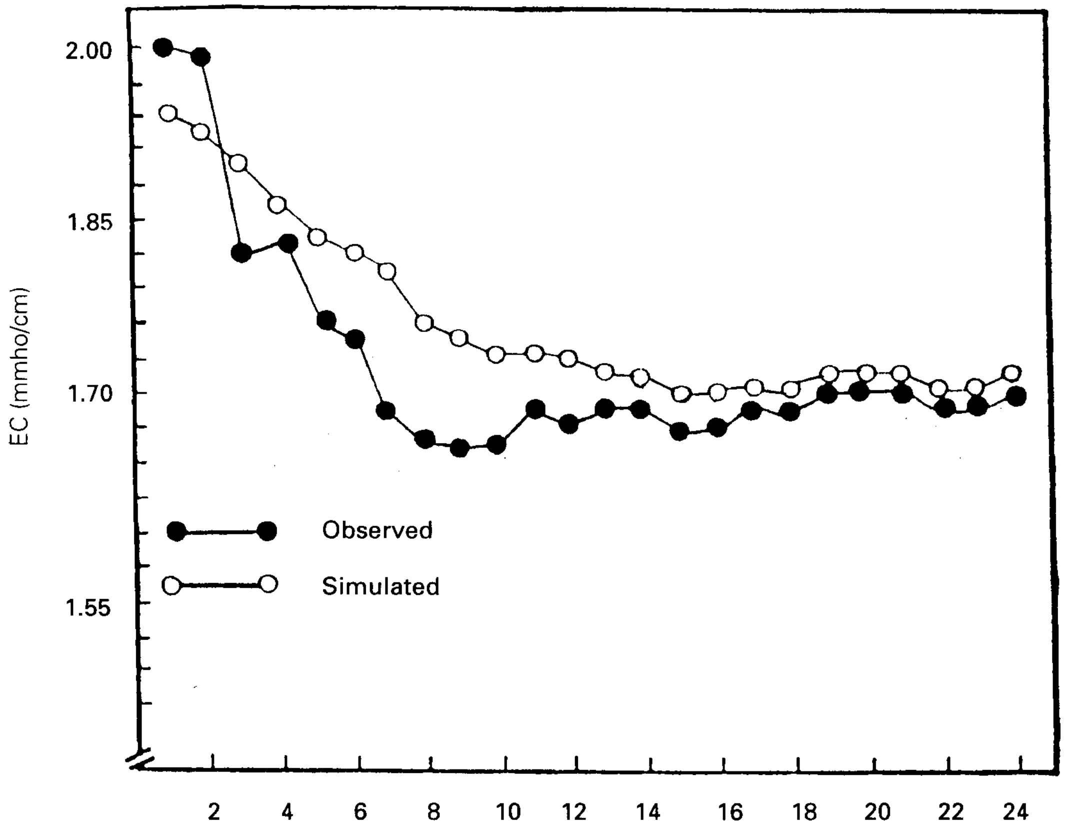

Fig. 8. Observed and simulated EC over a 24-day growing period in nutrient solution for pak-choi grown in a DRF hydroponic system. The nutrient concentration was 1.7 mmho/cm at the beginning of this period. An additional 3.4 mmho/cm of concentrated nutrient solution was the supplied automatically from the upper nutrient tank

Table 8. The pH, EC and fresh weight of pak-choi grown under different nutrient conditions

Temperature of nutrient solution	Concentration of nutrient solution	Fresh weight (gm/plant)	pH	EC (mmho/cm)
17-21°C	No control	41.9	7.8	1.1
	Automatic control	63.4	6.0	1.7
27-31°C	No control	39.7	4.9	2.9
	Automatic control	61.9	6.0	1.7

Table 9. The seasonal productivity of various vegetable grown in DRF hydroponic system

Vegetable	Productivity		
	gm/plant	kg/panel	ton/0.1 ha
Brassica species	41.2-58.2	5.9-8.7	3.1-5.8
Leafy lettuce	51.3-71.3	7.4-10.3	3.8-5.4
Butterhead lettuce	199	1.4	1.8
Crisp lettuce	660	4.7	6.6
Edible amaranth	40.2	5.8	3.0
Water convolvulus	100.3	14.4	7.5
Spinach	36.4	4.2	2.2
Garland chrysanthemum	36.2	5.2	2.7
Chinese leek	24.3	1.8	1.2
Cucumber	2480	6.1	7.7
Tomato	650	2.7	3.6
Muskmelon	730	1.6	2.0

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Table 10. Estimated cost for constructing a DRF hydroponic vegetable factory (43.6 x 19.78 m^2)

Item	No. required	Unit Price	Total
Culture bed	264	12	3168
Black PE sheet	12	67	804
Panel	528	1.8	950.4
Aspirator	48	7.5	360
Nutrient exchange box	12	32	384
Nutrient supply pipe and parts	12	71.5	858
Reservoir	1	1500	1500
Upper nutrient tank	1	1000	1000
Lower nutrient tank	2	68	136
Pump	2	170	340
Nutrient concentration controller	2	100	200
Piping framework for greenhouse	24	750	18000
Total			US$27,700.4

Table 11. Annual profit from a DRF hydroponic vegetable factory (43.6 x 19.78 m^2)

Gross income	
Annual production	86.6 kg/day x 365 day/year = 31,609/year
Unit price	US$1.13/kg
Income	US$1.13/kg x 31,609 kg/year = 35,718.2
Costs	
Seed	151
Polyfoam blocks	1,527.7
Electricity	1,509.4
Nutrients	3,344.3
Water	71.5
Chemicals	226.4
Salary	9,056.6
Postharvest vegetable losses	1,789.2
Packaging materials	2,504.8
Depreciation of equipment	6,008.7
Subtotal	US$26,189.6
Net profit	35718.2 - 26189.6 = US$9,528.6

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DISCUSSION

Q. (E.S. Lim)
Could you please give us some indication of the size of greenhouse you would expect a grower to handle, and the price of the facilities for such an area?

A. In a hydroponics system of the type I have described, each person can take care of about 0.3 ha. I estimate that an economic size for a greenhouse would be about 30 m in length and 2.13 m wide, and would thus need four persons. The cost of a unit per 0.1 ha is about US$27,000.

Comment: (M.H. Jensen)
A closed system might be an advantage if there is air pollution, but closed systems may not suit some crops. Curcurbits such as cucumber and melon are more challenging to grow than leafy vegetables or solenaceous crops such as green pepper and tomato, which seem to do better in closed systems. We may need to look at open systems with media for curcurbits.

Another important point is that if algae are present, they support a small fly called the fungus gnat which can be a serious problem. The system has to be kept free of algae for this reason, and I noted that the excellent growers in Taiwan are managing to keep algae out of their hydroponics systems.

Q. In Table 11, the cost of depreciation of equipment seems fairly high. What does this item cover?

A. It covers replacement costs, and it is high because Taiwan's typhoons mean that the grower has to replace the plastic film every year. The PE shade net can also be destroyed by strong winds.

Q. What is the main advantage of your system compared to NFT and DFT?

A. The major advantage is that at high temperatures, the DRF system induces the growth of aeroroots. If any hydroponic system is to be used in the tropics, it must have the ability to induce aeroroots.