Economic, Environmental, and Natural Resource Benefits of Plastic Shelters in Vegetable Production in a Humid Tropical Environment

Lalit M. Arya
Edward L. Pulver
M. Th. van Genuchten

ABSTRACT. This paper reports the effectiveness of plastic shelters in overcoming soil-related and biotic constraints to vegetable production in Belize, Central America, where rainy-season tomatoes and sweet peppers are almost totally destroyed by geminiviruses. Use of pesticides is rampant, while rapid decline in soil productivity induces farmers to abandon previously used lands and clear new lands from virgin forests. We postulated that plants growing in the open-field environment are infected early by the soil-borne pathogens deposited on the plants from clouds of fine soil particles arising from the soil splash

Lalit M. Arya and Edward L. Pulver are affiliated with the Winrock International Institute for Agricultural Development, 38 Winrock Drive, Morrilton, AR 72110-9537.

M. Th. van Genuchten is affiliated with the U.S. Salinity Laboratory, ARS-USDA, 450 West Big Springs Road, Riverside, CA 92507.

Address correspondence to: Lalit M. Arya, U. S. Salinity Laboratory, USDA-ARS, 450 West Big Springs Road, Riverside, CA 92507 (Present address, E-mail:larya@ussl.ars.usda. gov).

The developmental research reported in this paper was carried out under the sustainable agriculture production program (SAP) of the Natural Resource Management and Protection Project (NARMAP), Belize, Central America. Funding for the project was provided by the U.S. Agency for International Development (USAID). The project was implemented jointly by the Government of Belize (GOB), the World Wildlife Fund (WWF), and the Winrock International Institute for Agricultural Development (WI). Funds for field evaluation of the plastic shelter technology were provided by the United Nations High Commission for Refugees (UNHCR). All assistance received is gratefully acknowledged.

during high-intensity rainfall. The products of fungal and bacterial decay attract white flies (the vector for geminiviruses) and plants already weakened by the infection succumb easily to the viruses. A production system in which plant and soil surfaces are protected from direct rainfall using plastic shelters, was designed and field tested with tomatoes and sweet peppers. On average, plastic shelters increased tomato and sweet pepper yields by 169% and 96%, respectively, without any use of pesticides. Weed growth under the shelter was negligible, and plants maintained greenness and production well into the fourth month after transplanting. In contrast, open-field plots were infested with weeds, and plants were completely destroyed by the middle of the third month. The number of white flies visiting the plastic-shelter plants was only about 28% of that in the open-field. We conclude that total protection of soil and plant surfaces from rainfall is the most effective plant protection measure. The proposed system uses small land area on a continuous basis, provides stable production, requires little or no plant protection chemicals, and raises farmer income.

KEYWORDS. Humid tropics, biotic stresses, soil productivity, plastic shelters, vegetable production, plant protection, rural income, sustainability, environmental and natural resource protection

INTRODUCTION

Vegetable production is a significant farming enterprise in the humid tropics, especially for small farmers. Vegetables are an important source of food and nutrition, and provide cash income. However, a prolonged wet season and high rainfall intensities have a serious negative effect on vegetable yield and quality (Arya and Pulver, 1993; Pulver et al., 1995). On one hand, low light intensity has a negative effect on plant production processes; on the other, excessive wetness and warm temperatures encourage incidence of insect pests and diseases. High-volume, high-intensity rainstorms cause physical damage to plants. Young seedlings and flowers are particularly affected. Pollens are often washed off and fruit set is poor. Soil splash produced by raindrops disperses soil particles into the plant canopy, thereby depositing soil-borne organisms on leaf surfaces. The wet foliage provides an ideal surface for disease organisms to flourish. Moreover, frequent saturation of soil (even if temporary) leads to intermittent exclusion of oxygen, resulting in an unfavorable soil environment for root growth and plant functions (Else et al., 1995).

Thus, vegetable plants growing under high rainfall conditions are subjected to several simultaneous stresses, often resulting in heavy dependence on plant protection chemicals. To unsophisticated farmers, all symptoms of poor plant health appear to be due to pests and diseases. However, chemicals are easily washed off where rainfall amounts and frequency are high. As a result, frequency of pesticide application increases. Washed-off chemicals flow with surface runoff and also into the soil where they migrate with subsurface flow (Smith et al., 1993). Thus, the risk of soil and groundwater pollution is high (Hall and Pulver, 1994). Hence, the net return on labor is small, and excessive use of chemicals raises serious environmental and human health issues (Weber, 1987). Local production fails to meet the market demand. As a result, consumers needing vegetable supplies on a consistent basis (e.g., hotels and restaurants) choose to depend on imported vegetables, even during part of the year when local supplies may be adequate.

Rapid disposal of rainfall via internal drainage is a common feature in highly weathered soils of the humid tropics (Uehara and Gilman, 1980; Dierolf, 1992; Arya et al., 1998; Arya et al., 1999). Soil erosion, therefore, is not a serious issue when adequate ground cover is present. However, internal drainage of large volumes of water also removes readily soluble nutrients (Dierolf et al., 1997; Arya et al., 1999). Depletion of base cations means not only poor fertility, but also increased acidity and aluminum toxicity (Wade et al., 1988). Under these conditions the land quality degrades rapidly from its status prior to land clearing (Arief and Zubaidah, 1989; Arya and Pulver, 1993). Soil amendments such as lime and fertilizers become a necessity if the land is to be cultivated on a continuous basis.

Because of poor land quality and excessive wetness, fields often become heavily infested with weed species that are adapted to soil and environmental conditions. Weeds compete for space and nutrients (Lambert and Arnason, 1980) and are difficult to eradicate. Weeding costs add to the overall cost of production. Additionally, cultivation of fields to remove weeds during the rainy season increases the risks of erosion. Chemical weed control is expensive and suffers the same fate as pesticides applied as foliar spray.

The above constraints place a corresponding burden on the natural resources. First, because of poor yields a large acreage needs to be planted, which in turn causes larger land areas to be affected. Second, the rapid decline in productivity induces farmers to abandon current lands and clear new lands from virgin forested areas. The latter is common in parts of Central and Latin America, humid tropical Africa, and Southeast Asia, where availability of land and local land tenure systems permit slash/burn and shifting cultivation (Arya and Pulver, 1993; Pulver and Arya, 1993).

The foregoing observations imply that protecting vegetables from high intensity rainfall can result in economic, environmental, and natural resource benefits. Protection from the destructive effects of rainfall also means a stable production system capable of supplying the market demand on a consistent basis. In this paper we report the results of a pilot project in Belize, Central America, where the authors evaluated the feasibility of intensifying vegetable production using plastic shelters. Such shelters are in widespread use in temperate regions, where they are referred to as "high tunnels."

MATERIALS AND METHODS

Background, Physical Environment, and Constraints to Vegetable Production

The developmental research reported in this paper was carried out under the aegis of the Natural Resource Management and Protection Project (NARMAP), Belize, Central America. Sustainable agriculture production (SAP) was an important element of this project, and was focused on areas where agricultural activities posed a serious threat to natural resources, particularly protected forest reserves. The program covered three districts–Cayo, Stann Creek, and Toledo. Baseline surveys and analyses of biophysical and socioeconomic constraints provided the basis for technological interventions (Arya and Pulver, 1993; Pulver and Arya, 1993). Vegetable production appeared to be an important enterprise in the Cayo District. Approximately 55% of the farmers in this district grow vegetables for commercial production. Tomato and sweet pepper are the most important crops. Production, however, is erratic and suffers from numerous soil- and weather-related problems and biotic stresses. Consequently, importation of fresh vegetables becomes necessary.

Geminiviruses pose the most serious biotic constraint to production of tomato and sweet pepper. These viruses are transmitted by white flies and have a devastating effect on the crop. Farmers use chemicals indiscriminately to control the white fly. A survey of pesticide usage in Cayo (Quiroz and Pulver, 1993) indicated that farmers use 13 different insecticides and 7 fungicides. The number of applications range from 12 to 42 for tomatoes and 21 to 75 for sweet peppers, depending on whether the applications are on an every-other-day or weekly basis. Important results of the survey are presented in Table 1. Data show high frequency of applications and substantive investments in plant protection.

Soil and weather conditions for the Cayo District have been described by King et al. (1992). The rainy season in the district normally starts mid-June and lasts through January. Rainfall amounts vary from 2500 to 3000 mm/year, with torrential rainstorms being quite frequent. Atmospheric humidity

TABLE 1. Application frequency of pesticides in the Cayo district and estimated cost/ha of four selected pesticides (Quiroz and Pulver, 1993).

Crop	Crop duration (days)	Spray interval	Number of sprays	Estimated cost (BZ $/ha)¶			
				Tamaron	Thiodan	Applaud	Ambush
Tomato	85	weekly	12	195	561	482	652
		2-day	42	680	1,962	1,685	2,281
Sweet	150	weekly	21	339	981	843	1,142
pepper		2-day	75	1,213	3,504	3,010	4,075

¶ Estimated cost if a single pesticide was used for the entire growing season. 1 US $ = 2 BZ $.

remains high and sunshine hours range from 4.8/day in November to 8.1/day in April. Pan evaporation averages about 1600 mm/year. Shallow soils with limestone rocks dominate the area.

Protected Cultivation of Vegetables

The Plastic Shelter: As discussed earlier, we observed a high negative correlation between vegetable production and wetness of the land and atmosphere. Our objective, therefore, was to minimize or eliminate the rainfall factor. Plastic shelters offered the most efficient means of achieving the objective. The shelter (Figure 1) covered a land surface area of 3.66 m by 15.24 m and was constructed by stretching a plastic sheet over a frame that consisted of a series of U-shaped arches made of 2.54 cm O. D. by 6.1 m long PVC pipes. The arches were spaced 1.52 m apart and fastened to wooden or galvanized steel posts using clamps and screws. The edges of the plastic sheet terminating on the sides were folded and stapled on 2.54 cm by 10 cm wooden flats attached to the posts along the length of the structure. A thin and narrow strip of wood was nailed over the stapled edges to firmly hold the plastic sheet in place. The edges of the plastic sheet at either end of the structure were folded around the end arches and fastened using duct tape and a PVC pipe clamp. The clamp was made by vertically cutting a 7.62 cm long PVC pipe with 3.18 cm diameter. The cut was made at about 1/3 of the diameter, with the portion retaining the 2/3 of the diameter being used as a slip-on clamp.

The height and width of the structure were limited by the size of the plastic sheet, which was available in rolls of 6.1 m width. We used ultraviolet-resistant plastic material (Tufflite, 3-year life) manufactured by Monsanto Company[1] in the United States. To minimize the effect of wind, the longer axis was posi-

1. Mention of a company name or product does not imply endorsement by the authors, U.S. Government, or any of the collaborating organizations.

tioned along the prevailing wind direction. The peak height of the structure at the center was 2.74 m on the leeward side and 2.44 m on the windward side. The purpose of the sloping roof was to cause air inside the shelter to move rapidly. To further enhance aeration inside the shelter, the vertical space on the sides was kept open up to a height of about 75 cm. Although a shelter of almost any length could be constructed, we kept the length short (15.24 m) to enhance air movement and minimize heat buildup. Material and costs for building a 3.66 m by 15.24 m plastic shelter are presented in Table 2.

Water Management: Because rainfall was eliminated, we needed a system for irrigation. For this purpose we attached a gutter to the posts on both sides of the structure to capture rainwater that flowed from the plastic roof. The gutters terminated in 220-liter drums. Water collected in the drums was used for hand-watering plants as needed. Other water-holding devices, such as

TABLE 2. Material and costs for building a 12 ft by 50 ft plastic shelter.

Material[§]	Quantity	Cost, BZ $[¶]
(A) USING GALVANIZED STEEL POSTS		
1 1/4″ galvanized steel pipes @ $ 80 per 20′ length	5 lengths	400.00
1 1/4″ clamps @ $0.40 each	22	8.80
1″ × 20′ schedule 40 PVC pipes @ $ 13.10 each	11	144.10
1/2″ wood screw @ $ 0.05 each	44	2.20
1/4″ × 1/2″ tapping screw @ $0.05 each	22	1.10
1/4″ × 2 1/2″ bolts and nuts @ $0.175	44	7.70
Plywood nails @ $ 4.00 per lb.	1/2 lb.	2.00
3″ nails @ $ 2.00 per lb.	2 lbs.	4.00
1″ × 4″ × 6′ lumber @ $1.29 per piece	17 pieces	21.93
Thin wooden strip @ $ 0.05/ft	100	5.00
1 1/4″ schedule 40 PVC pipe @ $15.00 each	1	15.00
Duct tape @ $ 5.00 per roll	1 roll	5.00
Plastic cover @ $400 per 20′ × 100′ roll	20′ × 50′	200.00
Guttering for collecting rainwater @ $ .50/ft	100′	50.00
Water collection drum @ $10.00 each	2	20.00
Labor @ $ 20.00/man day	3 man days	60.00
Total cost		**946.83**
(B) USING WOODEN POSTS (other costs remain unchanged)		
4″ × 4″ × 5′ wooden posts @ $3.85 each	22	84.70
Total cost		**631.53**

[§] 1″ = 2.54 cm, 1′ = 30.48 cm; [¶] 1 US $ = 2 BZ $.

plastic-lined pits or large tanks buried in the ground, are also feasible. Our collection system was quite adequate for the local conditions.

Plot Preparation: The soil under the plastic shelter was deep-forked and watered with a hose to increase soil wetness. Two days later the soil was pulverized and raked to achieve a relatively level surface. Debris and live weeds were removed. The plot was fertilized by incorporating approximately 500 lb of farmyard manure and 10 lb of mixed NPK (13:13:13) fertilizer. The nutrient composition of the farmyard manure was unknown. A similar plot was prepared in the open field some distance away from the plastic shelter. Both plots were left undisturbed until planted.

Test Crops: Because of the initial cost of the shelter and intensified management, it was necessary to consider only high-value cash crops. Tomato and sweet pepper are the most valued vegetable crops in Belize, and these are also the crops most seriously affected by the geminiviruses. We, therefore, chose these two crops for our trials. For both crops, varieties chosen were those grown by local farmers and no specific importance was attached to variety selection at this stage of the trial.

Production of Seedlings: Tomato and sweet pepper seeds were densely sown in a sand box. The box was watered to saturation and covered until the seeds germinated. The seedlings were transferred to the soil medium in paper bags when they attained a height of 1 to 2 inches. The soil medium consisted of fertilized and pulverized topsoil (7 parts soil + 3 parts sand + 1 part chicken manure). Although sterilization of soil medium is highly desirable, it was not done in this trial. Newspaper bags (7.62 cm diam. × 10 cm deep) were prepared by rolling newspaper around a PVC pipe and taping the seam. The bags were set in trays in an upright position, filled with the soil mixture, and watered. When watered, the paper did not dissolve although some of the paper was torn during the period following the transfer of seedlings. However, seedling root growth kept the soil block intact.

Protection from White Flies: A factor of interest was the protection of seedlings from white flies that transmit the geminiviruses. Plant protection experts working on geminivirus problems in Cental America recommend protecting seedlings from white flies for a period of 30 to 35 days. Early protection presumably enables the plants to better tolerate virus infection and maintain productivity. An assessment of this technique was made, both under the plastic shelter and under the open-field conditions. One half of the trays with seedlings in paper bags were placed under a 32 by 32 mesh (i.e., 159 holes/cm^2) nylon screen to protect the seedlings from white flies. The screen was stretched over a protective frame built over the trays. The plants were watered with a spray hose as needed.

Seedlings were transplanted under the plastic shelter and in the open filed plot when they attained a height of about 20 cm. Plant spacing was 45 cm ×

45 cm. Each of the tomato plants were provided with a stake for support. Suckers in the tomato plants were pruned below the first flower cluster. Plants in the open field received water from natural rainfall while those under the plastic shelter were hand-watered at the base of the plant. It was necessary to ensure that plant foliage under the plastic shelter remained dry. Plants were fertilized once and weeding was done as necessary. Use of pesticide was not permitted unless absolutely necessary.

Trials were conducted at four locations: Santa Elena, Armenia, and Siete Millas in the Cayo District, and at Melinda in the Stann Creek District. Post-transplanting observations included yield data, counts of white flies, incidence of viral infection, and general browning and senescence. Rainfall data (Table 3) for the nearest weather station were obtained to relate plant growth and production to the severity of rainfall.

RESULTS AND DISCUSSION

Impact on Crop Productivity

Table 4 presents fruit yield data for three tomato and two sweet pepper trials. The data show a dramatic effects of the plastic shelter on production. Tomato yields under the plastic shelter increased by 122% at St. Elena, 1,200% at Siete Millas, and 57% at Melinda. Sweet pepper yields under the plastic shelter increased by 705% at Armenia and 22% at Melinda. In comparison to other locations, yield increases at Melinda were modest. Rainfall amounts and the number of rainy days at this location were significantly less than at the other locations (see Table 3). Hence, it appears that yield differences between the plastic shelter and the open field are related to the severity of rainfall. Means of yield data across the locations show that, on average, plastic shelters increased tomato yields by 169% and sweet pepper yield by 96%.

Growth Environment and Symptoms of Plant Health

A comparison of plant health and disease symptoms for tomatoes is presented in Figures 2 and 3. Fifty days after transplanting (Figure 2) the lower half of the tomato canopy in the open field exhibited a brownish/black appearance, indicative of severe fungal and bacterial infection. The upper part of the canopy exhibited a pale green color with numerous curly leaves and cankerous spots indicating viral infection. In contrast, plants under the plastic shelter remained healthy and uniformly green with only a few cankerous spots on the new leaves. Ninety days after transplanting (Figure 3) plants in

TABLE 3. Rainfall during the growing season from transplanting to harvest, al four locations.

Location: St. Elena, Cayo Crop: Tomato Transplanted: 15 Aug. '94 Harvest: 13 Oct.-9 Nov. '94			Location: Siete Millas, Cayo Crop: Tomato Transplanted: 25 Aug. '94 Harvest: 10 Feb.-15 Mar. '95			Location: Melinda, Stann Creek Crop: Tomato Transplanted: 21 Dec. '94 Harvest: 17 Feb.-15 Mar. '95			Location: Armenia, Cayo Crop: Sweet pepper Transplanted: 3 Nov. '94 Harvest: 26 Dec. '94-31 Jan. '95		
Week	Rainfall (mm)	Rainy days	Week	Rainfall (mm)	Rainy days	Week	Rainfall (mm)	Rainy days	Week	Rainfall (mm)	Rainy days
1	14.0	6	1	31.7	5	1	0	0	1	63.4	7
2	38.5	3	2	65.5	6	2	16.8	1	2	36.8	4
3	35.4	5	3	8.4	4	3	49.1	3	3	3.1	2
4	24.8	6	4	23.6	3	4	0	0	4	23.5	4
5	7.9	4	5	0.2	1	5	73.2	4	5	31.9	4
6	66.8	4	6	20.6	2	6	1.4	1	6	50.5	4
7	80.6	4	7	22.6	5	7	38.8	4	7	30.8	5
8	11.6	4	8	0	0	8	0	0	8*	0.2	1
9*	4.4	3	9	52.4	3	9*	26.6	3	9	20.6	2
10	37.5	3	10	18.6	3	10	8.5	3	10	21.9	4
11	61.8	4	11*	60.8	2	11	6.5	2	11	0.7	1
12	85.7	7	12	0.3	1	12	23.5	3	12	11.4	2
			13	28.2	4				13	58.4	2
			14	8.1	3						
			15	0.3	1						
			16	0.3	2						

* Start of harvest.

TABLE 4. Effect of plastic shelter on production of tomato and sweet peppe at four locations

	Yield, kg/m^2					
	Tomato			Sweet pepper		
Location	Plastic shelter	Open-field	% increase	Plastic shelter	Open-field	% increase
St. Elena, Cayo	4.80	2.16	122	–	–	–
Siete Millas, Cayo	6.36	0.49	1,200	–	–	–
Melinda, Stann Creek	5.62	3.59	57	4.34	3.55	22
Armenia, Cayo	–	–	–	3.46	0.43	705
Average	5.59	2.08	169	3.90	2.00	96

the open field had entirely blackened, whereas those under the plastic shelter maintained visible greenness although some senescence was noticeable. Under the plastic shelters, secondary flowering and fruiting continued well into the fourth month after transplanting.

The above observations, though qualitative in nature, lend support to the hypothesis that plants exposed to direct rainfall are infected early in the season, by soil-borne organisms, and succumb to the virus soon after. The source of the soil-borne organisms appears to be the splash caused by the

FIGURE 1. Construction of plastic shelter: (a) frame (b) shelter with plastic cover

(a)

(b)

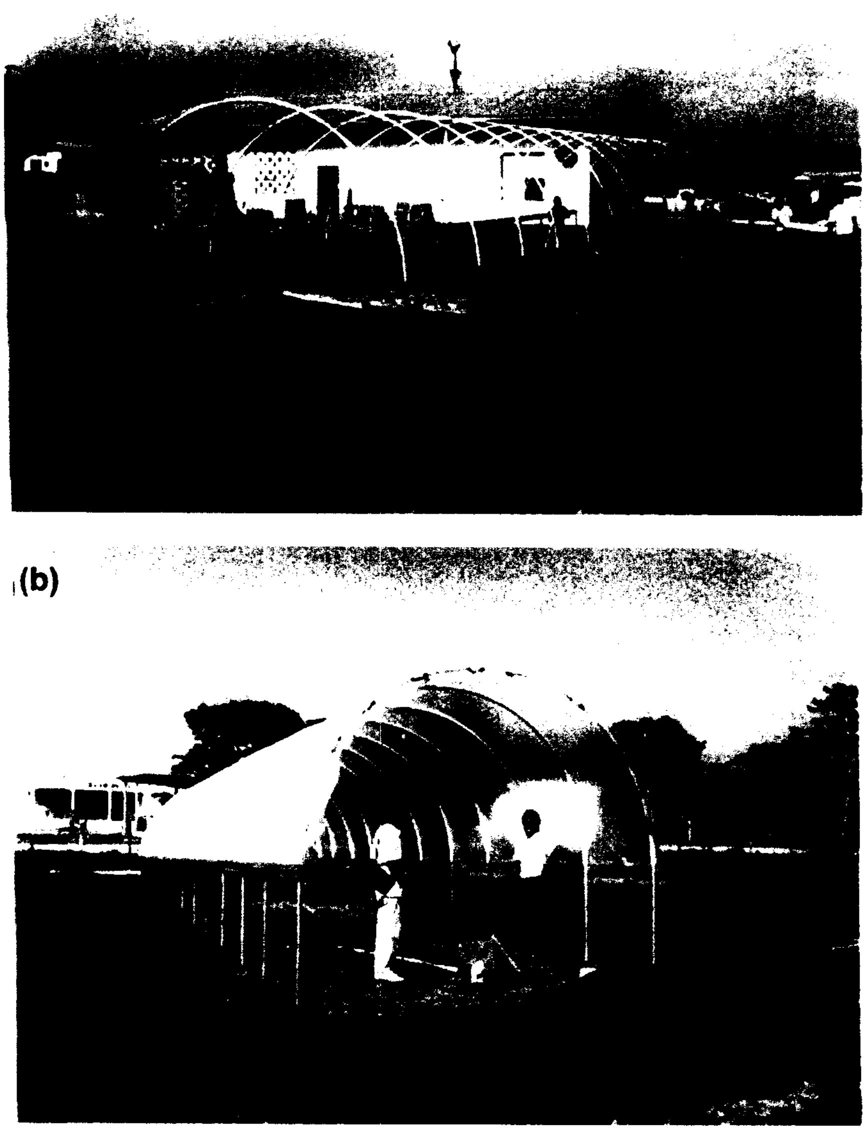
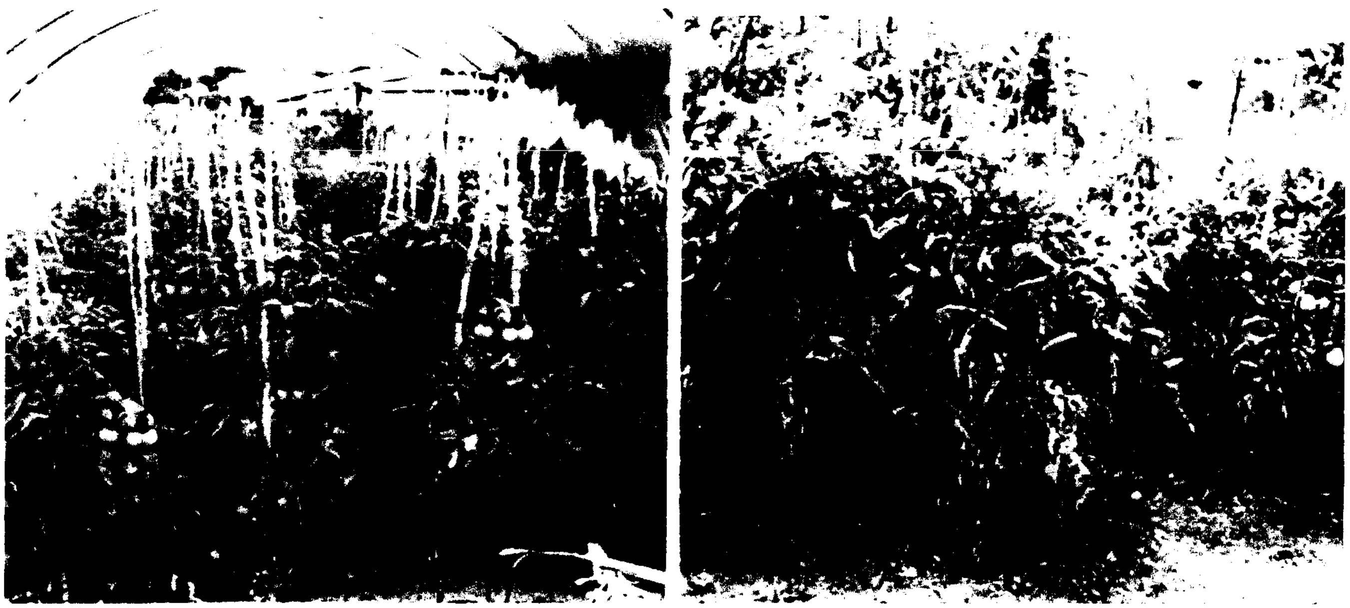


FIGURE 2. Effect of plastic shelter on tomato gorwth and production in a humid tropical environment. (Belize, Central America, 1994-95)

50 days after planting



Plastic Shelter | Open Field

FIGURE 3. Effect of plastic shelter on tomato growth and production in a humid tropical environment. (Belize, Central America, 1994-95)

90 days after planting

Plastic Shelter — Open Field

beating action of tropical rains. Warm temperatures and wetness of the canopy favor the growth and proliferation of disease organisms. In comparison, plant foliage under the plastic shelter remains dry and free of soil particles. Even if some soil particles are deposited on the leaves via wind, lack of moisture on the leaf surfaces minimizes the effectiveness of potential disease organisms.

Additional factors contribute to the overall favorable environment under plastic shelter. Because plants under plastic shelters were selectively hand-watered, weed problem was negligible. In contrast, open-field plants were infested with weeds, thus requiring frequent weeding. Weeds also serve as host to a variety of pest and disease organisms. Soil under the plastic shelter was never excessively wet, whereas the open field soil experienced intermittent saturation and lack of aeration. Fertilizer nutrients applied to the soil under the plastic shelter were most likely also better conserved and utilized, whereas those in the open field were subject to rapid leaching (Dierolf et al., 1997; Arya et al., 1999). The plastic shelter probably also modified the light, air-temperature, and humidity factors. However, it was not possible for us to make detailed measurements of the physical and biological variables involved. Our trials were part of a three-year development project with limited manpower, material resources, and time.

Incidence of White Flies and Use of Pesticides

Because the plastic shelter was open from all sides, white flies were free to visit the plants under the shelter. However, visual observations and approximate counts indicated far fewer flies under the plastic shelter than in the open field. White flies were captured on 60 cm × 60 cm sticky wooden surfaces erected at three locations in each plot. Counts showed that white flies under the plastic shelter were only about 28% of those in the open-field plot. A detailed study of why the flies had preference for plants grown in the open field was not possible.

As expected, no pesticides were needed either for tomatoes or sweet peppers grown under the plastic shelter. In comparison, farmers applied excessive amounts of pesticide to their open-field crops. As an example, in the farmer-managed sweet pepper trial at Armenia, 18 applications of a mixture of fungicides and insecticides were given to the open-field crop. Even with these massive pesticide applications, the open-field sweet peppers yielded only 0.43 kg/m^2. In contrast, the yield under the plastic shelter was 3.46 kg/m^2 (Table 4). Open-field plants were severely infected with a complex array of diseases early during the vegetative stage. Rains were heavy at this location and showers occurred each day during the first week after transplanting (Table 3). Relatively better yields of field-grown tomatoes and sweet peppers at Melinda, Stann Creek were likely due the fact that the first heavy rain occurred only during the third week after transplanting, while this location also had many more dry days (Table 3).

Management Issues and Opportunities

The project did not run long enough to enable us to address all management practices. We used the local varieties and standard plant spacing, irrigation, and fertilizer practices. Even with local practices, gains in crop productivity from plastic shelters were phenomenal. Crop yields could be even higher by using improved varieties (e.g., high yielding and disease-resistant varieties), better water management (e.g., drip irrigation), optimum plant spacing under intensified management, and effective plant protection practices (e.g., virus free seedlings and treatment for soil nematodes). In the following we discuss some of these management issues based on the experience gained during the two cropping seasons.

Effect of Virus-Free Seedlings: It is claimed that virus-free seedlings lead to healthy growth during the early growth stages. While plants may get infected during the later stages, the impact on yield is minimal. The effect of protecting the seedlings from white flies was evaluated in four trials: two with tomatoes and two with sweet peppers. Results are presented in Table 5. In general, data show no clear positive effect of protecting the seedlings from white flies, except for one trial with sweet peppers in which the protected seedlings in the open-field produced 43% more yield. As expected, tomato and sweet pepper yields under the plastic shelter were significantly higher than those planted in the open-field environment, regardless of seedling protection.

Continuous Production: The effect of planting tomato after tomato on the

TABLE 5. Effect of protecting seedlings from white flies on the yield of tomatoes and sweet peppers grown under a plastic shelter and in an open-field environment.

	Yield, kg/m^2					
	Plastic shelter			Open field		
Crop and Trial No.	Seedlings protected	Seedlings un-protected	% diff.	Seedlings protected	Seedlings unprotected	% diff.
Tomato 1	5.05	4.56	10.7	2.26	2.06	9.5
Tomato 2	5.51	5.73	−3.8	3.78	3.39	11.2
Sweet pepper 1	3.57	2.84	25.9	–	–	–
Sweet pepper 2	4.26	4.43	−3.8	4.18	2.91	43.3

Tomato 1. St. Elena, Cayo; Tomato 2. Siete Millas, Cayo; Sweet pepper 1. St. Elena, Cayo; Sweet pepper 2. Armenia, Cayo.

same field was evaluated under a plastic shelter at St. Elena in the Cayo District, where a crop of tomatoes had previously been grown. Healthy, virus-free seedlings were planted in one half of the plot under the plastic shelter, whereas the other half was devoted to tomatoes grown in large plastic bags filled with soil without a previous history of tomato cultivation. Tomatoes planted in the plastic bag produced 4.88 kg/m^2 while those on the ground produced 3.69 kg/m^2–a reduction of 32%. These results merely serve to indicate potential problems that might develop from continuous production of a crop on the same field. A long-term, multi-location experiment may be needed to generalize these results. Similarly, an understanding of the nature of soil-borne pathogens, their effect on crop production, and methods to control them, will require more long-term, controlled studies.

The plastic shelter technology described in this paper facilitates intensive production, but also requires intensified management, including simple agronomy. To justify the cost of the facility, farmers should attempt to grow as many crops as possible. This will mean a short turn-around time between crops. Under such intensive production, soil-borne diseases and nematodes are likely to build up and limit productivity. The aim of protected cultivation is to remove as many yield restraining factors as possible, thus permitting crops to produce as much as possible. The data we obtained for all trials indicate that total protection from rainfall is by far the most important plant protection measure. However, we emphasize the importance of other plant protection measures. Our observations in Belize are based on data for only two seasons and a few locations. In the absence of long-term experiments, we recommend that seedlings be protected from geminiviruses, seedlings be grown in paper bags, and crop rotation or other soil treatments be practiced so as to minimize the build-up of soil borne diseases. Much evidence has been obtained indicating that large amounts of organic matter, farm yard manure, or poultry manure can provide effective control of soil-borne pathogens (Hoitink and Fahy, 1986; Linderman, 1989; Morant et al., 1997). Legume cover crops such as mucuna (*Stilozobium* spp.) seem to provide effective control of many soil-borne pathogens. Good crop rotation will also help minimize the problem (Rodriguez-Kabana and Canullo, 1992). High-value crops that are genetically unrelated (e.g., Solanaceae and Cruciferae) can be grown on a rotation basis where several plastic shelters are available. *Brassica* spp. appear to be especially effective against soil-borne pathogens (Sarwar et al., 1998). These practices will ensure optimization of benefits from protecting high-value vegetables from the damaging effects of rainfall.

Cost Considerations

The objective our developmental research was to establish the benefits of protecting high-value vegetables from the damaging effects of rainfall.

Hence, establishing the most economic means of construction was not the primary goal. Our initial design was established by trial and error. Material and labor costs per unit amounted to BZ$ 946.83 with galvanized steel posts, and BZ$ 631.53 with wooden posts (Table 2). Assuming that a farmer chooses the galvanized steel posts and obtains a loan to build the plastic shelter, his total cost at 10% interest per year, on a two-year loan, would be approximately BZ$ 1136 per unit. Production data (Table 4) show that a 46.5 m^2 space under the plastic shelter would produce 260 kg of tomatoes and 182 kg of sweet peppers. At BZ$ 4.4/kg for tomatoes and BZ$ 6.6 for sweet peppers, the gross revenue from one crop would be between BZ$ 1100.00 and BZ$ 1200.00. With these revenues the farmer could readily pay off the loan in 3 to 4 installments. Depending on how permanent a structure is, the construction costs can also be amortized over several years.

Construction costs can be further reduced. In many cases family labor would be used to do the construction. Also, the frame of the structure should last many years if properly built. The UV-resistant plastic cover has a 3-year life and would need replacement at a cost of BZ$ 200.00 per unit plus the labor cost. The plastic used in our experimental models was imported from the United States in small quantity, hence the cost was higher. If large quantities are imported, the cost to the farmer should decrease.

Other factors need to be considered in cost/benefit comparisons and analyses. Since rainfall is entirely eliminated, water management under the plastic shelter involves use of watering cans and manual labor. This means that water should be available in close proximity to the plastic shelter. This problem was solved by harvesting rainfall from the roof of the plastic shelter. The gutter attached on both sides to the lower part of the plastic shelter was effective in capturing and diverting rainfall to water storage drums or plastic-lined pits. The cost of adding the gutter was BZ$ 3.28/m or BZ$ 120/unit. We used a drip irrigation system in a few cases and found it to be the most effective system of irrigation under the plastic shelter. The system, however, requires pumping or raising the storage reservoir to enable gravity flow into the drip lines.

On the other hand, the average person-hours of labor needed under the plastic shelter is far less than is normally spent in the open-field environment. Because plants are watered using a watering can, only the individual plants receive water, while the rest of the soil surface remains dry. Consequently, weed growth is minimal and weed control costs are negligible. Moreover, no money or labor is spent on plant protection. Our experience, admittedly still limited, suggests that pesticide application under the plastic shelter is seldom warranted. Under the open-field environment, on the other hand, farmers apply from 12 to 42 applications of insecticides and fungicides to tomatoes, and 21 to 75 applications to sweet peppers (Table 1). These are prophylactic applications based on a every other day or weekly spray program. The average cost of the chemicals alone is BZ$ 35.33 per hectare per application.

Economic, Environmental, and Natural Resource Benefits

Reliable data on input and labor costs under the open-field environment were unavailable. Estimates from a baseline survey (Pulver and Arya, 1993) suggest that an average vegetable farmer in the Cayo District of Belize grosses about BZ$ 1200.00/year from vegetable production on about 0.4 ha of land. This is about the gross return that the farmer would get from one crop of tomatoes on a 46.5 m^2 land area, if plastic shelters are used, and good agronomy is practiced. In the open-field environment, a reasonable crop can be expected only during the transition from the wet to the dry season when the atmospheric and soil moisture conditions are relatively favorable. During the wet season, open-field plants experience the effect of intense rainfall several times during the cropping season (Table 3). In some cases, field-grown plants are almost entirely destroyed if high intensity rains are received soon after transplanting. Consequently, no more than two crops/year are possible in the open-field environment. In contrast, plastic shelters would permit year-round production if water and other inputs are provided.

Consistency of production is a significant advantage that would accrue from the use of plastic shelters. In Belize, local vegetable markets become oversupplied during certain times of the year (usually the transition from wet to dry season) while serious shortages occur at other times (usually during the prolonged wet season). During the rainy season only imported vegetables are available and often at extremely high prices. For example, tomato prices decrease to as low as BZ$ 0.9/kg during peak production, but rise to BZ$ 8-9/kg during the rainy season. A price of BZ$ 15-17/kg for sweet peppers is not uncommon during certain times of the year. Use of plastic shelters permits a more stable production that not only opens up new market opportunities, but also raises farmer incomes during typical off-seasons. Good quality produce during the rainy season would enable farmers to capture lucrative markets both at the village level and at non-conventional outlets, e.g., hotels and restaurants catering to tourists. An added advantage of produce grown under plastic shelters is the low pesticide usage. Pesticide-free vegetables can fetch a premium price in the market. Stable year-round production also means saving precious foreign exchange.

Land quality in humid tropical environments is preserved only as long as the land is under the native vegetation (Montagnini, 1990). Soil fertility is depleted rapidly after land clearing, and a variety of soil toxicity factors (especially low pH and excess accumulation of exchangeable aluminum) begin to develop (Arya et al., 1999). Maintenance of soil fertility is challenging. Rapid deep percolation of rainwater via internal drainage removes readily soluble nutrients. Frequent augmentation of soil fertility with fertilizers means that more nutrients will move to the groundwater. Occasional saturation and poor soil aeration lead to impairment of physiological functions in sensitive plants such as tomatoes and sweet peppers. Protected cultivation overcomes most of these soil-related problems.

Biotic factors (i.e., pests and diseases) pose the most serious constraint to vegetable production in the tropics. According to Kiss (1990), 278 diseases in tomatoes have been reported in the tropics compared to only 32 in temperate regions. As we have shown in the case of Belize (Quiroz and Pulver, 1993), rampant and massive applications of chemicals to combat pests and diseases has become a norm in many tropical regions. The effect of pesticides and other agrochemicals on human health and the ecosystem have become matters of great concern. The excessive use of chemicals has encouraged the emergence of more resistant strains of pests and diseases, while the chemicals themselves are causing great harm to the environment (DOE/GOB, 1992). In Belize, risks to terrestrial and marine environments from agrochemicals are considered to be high (Usher et al., 1994; Hall, 1994). The heaviest use of pesticides is associated with vegetable, banana, and citrus production. Experience with plastic shelters shows that a dramatic reduction in the use of pesticides can be achieved while enhancing quality and quantity of vegetable production.

For reasons discussed above, Belizean vegetable farmers do not get a reasonable return for inputs and labor they invest. Because the yields are poor, usually large areas are cultivated. In addition, rapid decline in productivity forces farmers to abandon previously cultivated lands and clear new lands from the forest. This is typical of a system where land is available for slash/burn and shifting cultivation. Our baseline survey (Pulver and Arya, 1993) indicates that, on a 5-year slash/burn cycle, an average farmer affects 5 times the land area he actually cultivates in a given year. Thus, traditional agriculture places a corresponding pressure on natural resources. Not only are large areas of natural vegetation being destroyed, lands brought into cultivation are often very fragile. With plastic shelters, the land area affected by vegetable production will be considerably reduced. As shown in Table 4, tomato yield under plastic shelters is approximately 2.7 times that in an open-field environment. In addition, three crops/year are possible under the plastic shelter, whereas only one reasonable crop can be expected in the open-field production system. An important point to note is that land degradation associated with high rainfall in an open-field environment is avoided under the plastic shelter, i.e., a given piece of land can be used on a permanent basis and high productivity can be maintained.

CONCLUSIONS

The most important finding from our work with plastic shelters is that controlled and intensive management of small areas in the humid tropics is more profitable and sustainable than poorly-managed large areas. As discussed in this paper, use of plastic shelters in vegetable production has numerous advantages. First, it makes farming operations independent from weather conditions (especially rainfall). Returns from each crop are assured. Returns are also high so that there is incentive to invest. Since leaching of nutrients is not a problem, the same piece of land can be used on a continuous basis. Three crops per year are possible under a plastic shelter as compared to one or at the most two under the open-field production system. Use of pesticides is eliminated or dramatically reduced. Quality and stability of production would enable farmers to capture market opportunities. Rural income would increase and the need for importing vegetables will be eliminated. Also, excess production may provide opportunities for processing.

The above advantages notwithstanding, this new technology cannot be implemented without sustained support. Technical know-how is lacking in most rural communities in Belize and other similar regions. Initial investment, even though small, is still a problem for most rural families. A workable credit system must be established. In addition, more research is needed to fully understand the microclimate under the plastic shelter, nutrient dynamics, soil-borne pathogens, and potential pest problems. Results reported in this paper are based on local cultural practices. Improved agronomy (i.e., variety, spacing, nutrient and water management, and pest control), appropriate for an intensified management system, offer additional opportunities to increase production and income.

REFERENCES

Arief, A., and Y. Zubaidah. 1989. Preliminary report on the second International trial on soil fertility of acid upland soils for rice. 1989 INSURF Workshop and Planning Meeting, Bangkok, Thailand. 30 August-1 September 1989.

Arya, L. M., T. S. Dierolf, A. Sofyan, I. P. G. Widjaja-Adhi, and M. Th. van Genuchten. 1998. Field measurement of the saturated hydraulic conductivity of a macroporous soil with unstable subsoil structure. Soil Sci. 163: 841-852.

Arya, L. M., T. S. Dierolf, A. Sofyan, I. P. G. Widjaja-Adhi, and M. Th. van Genuchten. 1999. Significance of macroporosity and hydrology for soil management and sustainability of agricultural production in a humid-tropical environment. Soil Sci. 164: 586-601.

Arya, L. M., and E. L. Pulver. 1993. On-site appraisal of target areas for sustainable agriculture production. Sustainable Agriculture Production Program: Natural Resource Management and Protection Project, Belize, Central America. Winrock International Institute for Agricultural Development, Arkansas, 50 pp.

Dierolf, T. S, L. M. Arya, and R. S. Yost. 1997. Water and cation movement in an Indonesian Ultisol. Agron. J. 89:572-579.

Dierolf, T. S 1992. Cation movement and management in an Indonesian Ultisol. Ph. D. Thesis. University of Hawaii, Honolulu, HI.

DOE/GOB, 1992. The Belize national report to the United Nations conference on the environment and development (UNCED). Department of the Environment, Government of Belize, Belmopan, Belize.

Else, M. A., W. J. Davies, M. Malone, and M. B. Jackson. 1995. A negative hydraulic message from oxygen-deficient roots of tomato plants: Influence of soil flooding on leaf water potential, leaf expansion, and synchrony between stomatal conductance and root hydraulic conductivity. Plant Physiol. 109: 1017-1024.

Hall, M., and E. L. Pulver. 1994. Assessments of the potential risks from agriculture on the coastal areas of the Stann Creek District. Sustainable Agriculture Production Program: Natural Resource Management and Protection Project, Belize, Central America. M. S. Thesis, Center for Environmental Technology, Imperial College of Science, Technology, and Medicine, London.

Hoitink, H. A. J., and P. C. Fahy. 1986. Basis for the control of soil-borne plant pathogens with composts. Ann. Rev. Phytopathol. 24:93-114.

King, R. B., I. C. Baillie, T. M. B. Abell, J. R. Dunsmore, D. A. Gray, J. H. Pratt, H. R. Versey, A. C. S. Wright, and S. A. Zisman. 1992. Land resource assessment of Northern Belize. Natural Resources Institute Bull. 43 (2 volumes). Overseas Development Administration, UK, 513 pp.

Kiss, A. 1990. Insect ecology and agricultural pest management. *In* Race to Save the Tropics. R. Goodland (Ed.). Island Press, Washington, D.C., pp. 81-99.

Lambert, J. D. H., and J. T. Arnason. 1980. Nutrient levels in corn and competing weed species in a first year milpa, Indian Church, Belize, Central America. Plant and Soil. 45: 415-427.

Linderman, R. G. 1989. Organic amendments and soil-borne diseases. Can. J. Plant Pathol. 11:180-183.

Montagnini, F. 1990. Ecology applied to agroforestry in the humid tropics. *In* Race to Save the Tropics. R. Goodland (ed.). Island Press, Washington, D. C., pp. 49-58.

Morant, M. A., J. L. Casasola, C. B. Brooks, E. T. Philip, V. G. Mitchell, and C. R. Orr. 1997. Poultry litter enhances soybean productivity in field infested with soybean cyst nematode. J. Sust. Agr. 11: 39-51.

Pulver, E. L., and L. M. Arya. 1993. Results of baseline survey in Toledo, Stann Creek, and Cayo Districts. Sustainable Agriculture Production Program: Natural Resource Management and Protection Project, Belize, Central America. Winrock International Institute for Agricultural Development, Arkansas, 76 pp.

Pulver, E. L., L. M. Arya, R. Quiroz, T. Ogaldez, J. Villafranco, and R. Juan. 1995. Use of plastic shelters for intensification of vegetable production under high rainfall conditions. Sustainable Agriculture Production Program: Natural Resource Management and Protection Project, Belize, Central America. Winrock International Institute for Agricultural Development, Arkansas, 33 pp.

Quiroz, R., and E. L. Pulver. 1993. Pesticide use in vegetables in the Cayo District. Sustainable Agriculture Production Program: Natural Resource Management and

Protection Project, Belize, Central America. Winrock International Institute for Agricultural Development, Arkansas, 9 pp.
Rodriguez-Kabana, R., and G. H. Canullo. 1992. Cropping systems for the management of phytonematodes. Phytoparasitica 20: 211-224.
Sarwar, M., J. A. Kirkegaard, P. T. W. Wong, and J. M. Desmarchelier. 1998. Biofumigation potential of brassicas. III. In vitro toxicity of isothiocynates to soil-borne fungal pathogens. Plant and soil 201:103-112.
Smith, S. J., A. N. Sharpley, and L. R. Ahuja. 1993. Agricultural chemical discharge in surface water runoff. J. Envir. Quality. 22: 474-480.
Uehara, G., and G. Gillman. 1981. The mineralogy, chemistry, and physics of tropical soils with variable charge clays. West View, Boulder, Colorado, pp. 101-102.
Usher, W., and E. L. Pulver. 1994. Evaluation of pesticide and fertilizer usage in bananas and potential risks to the environment. Sustainable Agriculture Production Program: Natural Resource Management and Protection Project, Belize, Central America. Winrock International Institute for Agricultural Development, Arkansas, 92 pp.
Wade, M. K., D. W. Gill, H. Subagjo, M. Sudjadi, and P. A. Sanchez. 1988. Overcoming soil fertility constraints in a transmigration area of Indonesia. Soil Management Collaborative Research Support Project, Bull No. 88-01. North Carolina State University, Raleigh, NC.
Weber, J. B. 1987. Pesticides: Food and environmental implications. *In* Proceedings of a Symposium jointly organized by IAEA and FAO, Neuherberg, 24-27 November 1987, pp 45-59.

RECEIVED: 07/30/99
REVISED: 02/28/00
ACCEPTED: 03/13/00