Protected agriculture using specialized structures has its roots in Roman agriculture and subsequent European plant-growing enterprises (Dab-yemple, 1973). Since those early beginnings, a multitude of structural types and systems have been used to modify the environment. Conceptually, they all incorporate the function of a modern-day greenhouse, which is the most common form of protected agriculture in the United States. Typically, the greenhouse structure has a permanent heating and ventilation system, is electrically powered, and provides for year-round production. Alternative protected growing systems are rowcovers and high tunnels, neither of which has mechanically assisted heating or ventilation features. Both systems are used primarily for season extension in spring or fall or both. More precise definitions for each are:

**Rowcover** A flexible, transparent material (polyethylene, polyester, or polypropylene) that is hoop-supported or floated over a row or rows of crops at planting (seeds or transplants). It remains on the crop for 2 to 4 weeks in the spring or longer in the fall or winter. Hoop-supported rowcovers also are known as low tunnels.

**High tunnel** A portable walk-in, greenhouse-like structure without a permanent electrically powered heating or ventilation system, covered with one layer of plastic, and sited on field soil. In the northern United States, use is primarily seasonal from early spring to fall. Winter use is quite feasible in areas with moderate climates.

While greenhouses may offer somewhat precise environmental control (at a high price), rowcovers and high tunnels are not nearly as precise and not nearly so expensive per unit of area. They are not intended to function the same as greenhouses. They are intended to ameliorate adverse environmental conditions and offer some control of insects, diseases, and wildlife. Additionally, rowcovers and high tunnels should be considered as tools in an overall management program encompassing mulches, soil type and typography, cultivars, environmental considerations, pests, marketing, and grower objectives. The low capital investment associated with these systems is especially important to new growers.

**ROWCOVERS**

A brief history of rowcovers has been reported (Wells and Loy, 1985). Worldwide use of rowcovers has grown dramatically as new types of materials have been developed and as new uses have been found (Jensen, 1988; Takakura, 1988) from the traditional hot tent to heated, air-supported systems (Jensen, 1966). From the outset, it should be emphasized that the primary function of rowcovers in most cases is not frost protection; rather, they serve to enhance growth during periods of low ambient temperature. For most rowcovers in use today, the maximum frost protection in the spring is 3 to 4°F (2 to 3°C) below ambient freezing temperature. Only with specialized, heavyweight covers is greater frost protection achieved.

**Types of rowcovers**

**Paper.** Early research involved translucent paper. In fact, celery growers have used paper rowcovers, but other materials essentially have replaced paper.

**Polyethylene.** Most polyethylene covers are 18 to 26 μm thick and are solid, slitted, or perforated. When solid covers are used, two 3-foot-wide pieces of plastic are supported with wire hoops and a wire running over the tops of the hoops. The lower edges of the cover are secured with soil and the two top edges are joined at the center wire and secured with common spring-loaded clothespins. To facilitate daytime ventilation, the cover is opened each morning by removing the clothespins. To conserve heat during the night, the covers are closed in early evening (Hall and Besemer, 1972). A major disadvantage of this system is the high labor requirement for daily ventilation and the risk of the covers blowing apart at...
night during gusty winds.

A variation on the theme was devised by Loy and Wells (1982) so that daily opening and closing could be eliminated. Using the concept of slit-film mulch (Smith, 1973), a slitted rowcover of one 6-foot-wide sheet of clear plastic was developed. The slits are 5 inches long, 0.75 inches apart, and are configured in two rows of slits 2 feet apart. Once the cover is in place over wire hoops, the cover is not manipulated in anyway until removal 2 to 4 weeks later. In a fictional sense, the slitted cover is a compromise between labor reduction (opening and closing of solid covers) and greater heat loss at night through the slits than through a solid cover.

Perforated covers typically have seventy-five 1/8-inch holes/ft² (eight hundred 9.5-mm holes/m²). These covers are either hoop-supported or are used in a floating mode directly over plants. They provide a warmer air environment during the day than slitted covers, but provide about the same amount of nighttime heat retention. Perforated covers are available as wide covers, up to 50 feet (17 m) wide and 3000 feet (900 m) long.

Polyester and polypropylene. The chemistry of these two covers is different, but the final usable products are very similar. The material of each is a spunbonded, lightweight fabric that is 0.5 to 0.6 oz/yard² (17 to 20 g/m²) for most uses, although the weight varies from 0.3 to 1.50 oz/yard² (10 to 50 g/m²) for specialized uses such as insect control with the lighter weight and frost protection with the heavier weight. The spunbonded feature (as opposed to woven) permits the deposition of small-diameter fibers into a fairly uniform fabric sheet, allowing for 80% light transmission as well as air and water permeability. These covers are ultraviolet (UV)-light-stabilized to prevent premature degradation under agricultural environments. Covers are available in widths from 6 to 50 feet (1.8 to 17 m). Regardless of width and whether the grower is covering a single row or multiple rows, these lightweight spunbonded covers are secured only along the edges, usually with soil. Therefore, the wider the cover, the less labor-intensive the installation. For example, a 40-foot cover is installed almost as quickly as a 20-foot cover.

Uses of rowcovers environmental modification

Temperature. Because rowcovers are used to extend the season, night temperature is frequently the focal point for temperature control. However, as discussed above, major frost protection is not feasible with these lightweight covers; only 3 to 4°F protection can be expected. The exception is with the 1.5 oz/ft² (50 g/m²) material, which is heavy enough to provide greater frost protection but is too thick to allow adequate light transmission; hence, early morning removal is necessary. However, there has been a recent introduction of a 1.25 -oz/yard² (42-g/m²) polypropylene that improves heat retention, yet allows 75% light transmission. The major benefit is realized as the temperature rises faster than the ambient temperature in the morning under covers (Wells and Loy, 1985) and is maintained longer in the afternoon. Because covers are left in place for 2 to 4 weeks, the daily accumulation of additional heat units contributes directly to enhanced growth. However, the downside of accumulated heat is excessively high temperatures under covers when ambient temperatures exceed 86°F (30°C). The blossoms of solanaceous crops are particularly sensitive to temperatures of this magnitude (Wolfe et al., 1989), whereas blossoms of cucurbits are more tolerant of high temperature.

Not only are the high and low temperatures affected by covers, but, apparently, they can moderate low temperature extremes in the soil. Seedlings of overwintering lettuce (seeded in the fill) were heaved out of the soil with alternate freezing and thawing while covered seedlings were not heaved or killed by winter temperatures at 0°F (-18C) (O.S.W., unpublished data).

Extension of the season in the fall is accentuated by covers because of the enormous amount of heat stored in the soil as compared to springtime soil heat accumulation. A single layer of spunbonded cover will protect mature pepper and tomato fruits from freezing temperatures down to about 25°F (-4°C), which is more than twice the protection afforded by covers in the spring.

Wind protection. Spunbonded rowcovers increased the growth of cucumber by reducing the windspeed under the cover (Schloup et al., 1991). When covers are supported by hoops, plants are protected from wind, blowing sand, and desiccation. It should be pointed out, however, that floating covers may damage the tender growing point of plants under extremely windy conditions. When such conditions prevail, the cover, whether narrow or wide, should be supported over the plants with hoops or other devices.

Rain protection. Hoop-supported covers shield plants from direct hits by rain droplets during stormy conditions. Even though the water penetrates the covers, the plants are protected from the sheer physical force of the rain. Because polyester and polypropylene do not absorb water, these covers do not become excessively heavy during rain or irrigation and, consequently, do not damage plants even though the cover is lying directly on the plants.

Pest protection. Spunbonded covers protect against some insects and insect-transmitted diseases by providing a barrier between the insects and the crop (Duchesne, 1990; Hemphill, 1989; Hough-Goldstein, 1987; Natwick and Durazo, 1985; Wells and Loy, 1985). A cover should not be used where there is the likelihood of overwintering insects emerging from the soil under the cover. Because of the favorable environment provided by the cover, the end result could be a serious insect problem before the insects are noticed. The under-cover environment is also very conducive to weeds. Without mulch or herbicides, weeds quickly proliferate and seriously compete with the crop. Even with herbicides, a higher application rate is needed to control completely the weeds that normally are controlled at a lower rate without a cover.

Economics of rowcover use

The number of variables associated with rowcover use are numerous; therefore, the individual user will need to workout the management and economics in light of the objectives of the farm or other growing unit. The average costs for cover alone are $500 (polyethylene) to $800/acre (spunbonded) ($1200 to $2000/ha). The cost of labor for installation varies widely depending on whether single rowcovers with supporting hoops are used or wide floating covers are ap-
Whereas greenhouses are geared to-
New England are as follows (Wells, 
features of a high tunnel as used in 
tunnels are easily portable in the sense 
are intended for season extension. High 
management differs considerably. 
low tunnels (single rows with a 
are results of enhanced growth; when 
these are combined with better mar-
ket opportunities, the added ben-
etits of covers may be determined.

HIGH TUNNELS

High tunnels fit into a crop man-
agement program somewhere between 
low tunnels (single rows with a 
rowcover) and greenhouses. They look 
like greenhouses and incorporate the 
basic concepts of a greenhouse, yet the 
management differs considerably.

Whereas greenhouses are geared to-
ward year-round production, tunnels 
are intended for season extension. High 
tunnels are easily portable in the sense 
of fast take-down and set-up, which is 
important for crop rotation. The basic 
features of a high tunnel as used in 
New England are as follows (Wells, 
1991 b):

1. A 14 x96-foot (4.3 x29-m) quonset 
style, metal- bow tunnel is a standard 
unit.
2. The bows are attached to metal posts 
(3.5 feet or 1.1 m long), which are 
then driven into the ground 2 feet 
(0.6 m).
3. The end walls are detachable or have 
doors large enough to accommodate 
a small tractor with tillage equip-
ment.
4. The plastic cover is 6-mil greenhouse-
grade polyethylene.
5. Trickler irrigation lines are laid, one 
line per row.
6. The soil and the trickler irrigation 
lines are covered with a sheet of 6-rol 
black plastic.
7. Ventilation is provided by roll-up 
sides using a sliding T handle (Fig. 
1).

The use of tunnels for food crop 
production in the United States is very 
limited. (However, high tunnels, gen-
erally called hoop houses, are used 
commonly for the overwintering of 
nursery stock.) In contrast, southern 
Europe, Asia, and Israel use high tun-
nels extensively. A cursory glance from 
the air in the Mediterranean region 
reveals hundreds of hectares of tunnels 
in concentrated locations. Despite the 
low use of high tunnels in the United 
States, research in New England indi-
cates that these structures have a high 
potential for meshing into integrated, 
intensive production of food crops 
This is especially true where direct 
selling is the primary marketing chain-
nel.

High-value crops such as tomato, 
pepper, cucumber, melon, summer 
squash, and cut flowers are suited ide-
ally for high-tunnel production. Gent 
(1991) found that high tunnels ex-
tended the production season of to-
mato by accelerating growth and rip-
ening. Pepper ripening also was ad-
vanced, but less than that of tomato.

High tunnels in New Hampshire ad-
vanced maturity of tomatoes by 32 
days compared to unprotected field 
tomatoes (Wells, 1991 b). In looking 
at the economic feasibility of produc-
ing tomatoes in high tunnels, Wells 
and Sciarabba (1991) calculated that 
the net return (after all expenses) for 
tomatoes was $0.71/lb based on the 
production of 2000 lb in a 14 x 96-
foot tunnel and at a retail selling price 
of $1.60/lb.

High tunnels are relatively inex-
pensive. Using 1991 figures, it cost 
$1.26/ft ($13.56/m) of growing area 
to erect a 14 x 96-foot (4.3 x 29-m) 
high tunnel, including labor costs. 
Because of the low capital investment 
and high returns, high tunnels provide 
a practical means of entry into inten-
sive crop production for new growers 
or others with limited capital assets.

Unlike some greenhouses, high tun-
nels do not qualify as taxable struc-
tures.

Overall, a high tunnel is a grow-
ing structure that protects against rain, 
wind, weeds, some insects, and dis-
eases. Not only are high tunnels useful 
for early spring/late fall growing, they 
are useful all summer long. With daily 
attention to ventilation (rolling up the 
sides each morning and rolling them 
down each evening), the tunnel envi-
ronment is very conducive to excellent 
crop growth. However, width is criti-
cal; when the tunnel is wider than 20 
feet, it is doubtful that adequate venti-
lation is attainable when outside tem-
peratures exceed 86°F (30°C). Length is 
not a factor in ventilation as long as the 
width is not excessive.

Summary

Rowcovers and high tunnels are 
economical systems for enhancing crop 
growth, extending the season, and as-
sisting growers in maximizing profits 
with intensive production practices. 
Based on grower adoption of rowcovers 
and high tunnels throughout the world, 
it seems reasonable to conclude that 
these production systems are integral 
to early production. High tunnel use 
in the United States is not nearly as 
prevalent as in other parts of the world, 
but, in the northeastern U.S., the in-
terest in high tunnels is growing rap-
idly. For example, in New Hampshire 
in 1988, only 15 high tunnels were 
used for vegetable production; in 1992, 
there were about 80.

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Fig. 1. A high tunnel with roll-up sales for ventilation.
Literature Cited


