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10 suitable.

11
12 The cool, short growing season characteristic of most of Canada limits commercial production of many
13 vegetable crops. Production of warm-season crops such as melons, peppers and tomatoes is particularly
14 difficult unless means are employed to improve the growing conditions. Plasticulture involves using
15 plastic soil mulches and crop covers to improve the microclimate surrounding the crop, thereby enhancing
16 earliness, improving yields and increasing profitability (Waterer, 1992, 2000; Wells and Loy, 1985;
17 Wittwer and Castilla, 1995). At present, low tunnels represent the standard method for using plastics to
18 enhance the growth of most vegetable crops (Wells and Loy, 1993). A low arch [typically less than 0.75
19 m (2.5 ft) tall] of perforated clear polyethylene or non-woven fibre is supported above the crop using wire
20 hoops. Typically, a single row of the crop is protected by each cover. By increasing air temperatures,
21 reducing wind damage and by providing a degree of frost protection, the low tunnels accelerate crop
22 development and extend the growing season (Waterer, 1992; Wells and Loy, 1985). However, low
23 tunnels have several limitations. Due to their small size, the low tunnels must be removed soon after
24 installation, otherwise they interfere with crop growth (Waterer, 1992). The small size of the low tunnels
25 also limits the cultural practices which can be accomplished with the tunnels in place; for example
26 weeding or spraying are impractical. Unusually warm spring weather can cause heat stress to the covered
27 crop unless the low tunnels are partially removed. Removal and reinstallation of the tunnels is however

1 labor intensive. The covers also must be removed to allow access to the crop by insect pollinators.

2 Finally, the materials used in low tunnels have a limited lifespan and typically new materials are used
3 every year. Adoption of low tunnel technology represents a substantial additional cost to the growers in
4 both the tunnel materials and the labor required for their installation and removal (Wells, 1996).

5 High tunnels are similar to low tunnels in design and function, except that; 1) one tunnel covers
6 several rows, 2) the high tunnels are large enough to grow the crop to full maturity under the tunnels, 3)
7 the tunnels are large enough to allow many cultural practices to occur with the tunnels intact and 4) the
8 tunnels remain in one spot for several cropping seasons (Wells, 1996; Wells and Loy, 1993). The high
9 tunnel structure consists of arch ribs driven into the ground covered with a single layer of greenhouse-
10 grade polyethylene. There are no artificial heating or cooling systems. Rolling up the sides or opening the
11 end doors of the high tunnels provides both ventilation and access to the crop by pollinating insects. At
12 the conclusion of the growing season, crop residues are removed and the soil in the high tunnels is tilled in
13 preparation for the next season. The covers are left in place over the winter. The initial cost of purchasing
14 and installing the high tunnels is higher than traditional low tunnels but the economics of production with
15 high tunnels may still be favorable if they increase yields or allow growers to access markets at times
16 when prices are at a premium (Hochmuth et al., 1998; Wells, 1996; Wells and Loy, 1993). If the high
17 tunnels are durable, the costs of materials and installation may be amortized over multiple growing
18 seasons.

19 High tunnels are used extensively in the Middle East and Europe for the production of melons,
20 tomatoes and other high-value warm-season produce (Wittwer and Castilla, 1995). To date, utilization of
21 high tunnels has been limited in North America, although the potential benefits of this technology have
22 been demonstrated (Lamont et al., 2001; Wells and Loy 1993). Penn State University has recently
23 established the High Tunnel Research and Education Center to research production and management
24 issues for high tunnels (Lamont et al., 2001). Profitable operation of the high tunnels hinges on
25 maximizing productivity within the constrained space available (Lamont et al., 2001; Loncaric et al.,

1 1999), with a corresponding focus on high value crops which command price premiums for off-season
2 production. This project compared yields, crop quality and production economics of the high tunnel
3 system versus traditional low tunnels over three years using warm-season vegetable crops in
4 Saskatchewan, Canada - a region with a cool, short growing season.

6 **Materials and methods**

7
8 The trials were conducted at two sites in Saskatchewan (Outlook and Saskatoon), Canada during the 1998,
9 1999, and 2000 cropping seasons. The crops selected for testing (muskmelon, pepper, and tomato) are
10 high-value vegetables, responsive to enhanced growing conditions. There is a significant demand for these
11 crops outside of the window provided by traditional field production. Muskmelon (cv Earligold) was
12 grown at both sites, but tomato (cv. Roadside Red and Spitfire) was only grown in Saskatoon and pepper
13 (cv. Valencia, Ultraset, Whopper and Superset) was only grown in Outlook. The cultivars for each crop
14 were selected based on superior performance in previous field trials (Waterer and Bantle, 1998).

15 The soil in both the high tunnels and the low tunnel plots was prepared by rotovating and
16 incorporating sufficient fertilizer to raise soil fertility levels to those recommended for irrigated vegetable
17 production [100 kg ha^{-1} (89.2 lb/acre) nitrogen (N) and 59 kg ha^{-1} (52.6 lb/acre) phosphorus (P)](Millar,
18 1988). Plastic mulch [IRT (Ken-Bar Products, Reading, Mass.), 1 m (3.3 ft) wide,] was laid on 1.4 m
19 (4.59 ft) centers in both the high and low tunnel plots. The mulch was applied in advance of planting to
20 encourage soil warming. Drip irrigation tube [0.34 gal/min (1.287 L min^{-1}), T-Tape, San Diego, Calif.]
21 was installed under the mulch. In last week of May, once the risk of spring frost had largely passed,
22 greenhouse-grown seedlings of the test crops were transplanted into both the high and low tunnel
23 treatments. The peppers and tomatoes were 4 weeks old at transplanting, while the muskmelon seedlings
24 were 14 d old. In-row spacings were; tomato 45 cm (17.7 inches), pepper 15 cm (5.9 inches) and melon
25 30 cm (11.8 inches). The resulting plant populations [$15,870/\text{ha}$ (6,423/acre), $47,620/\text{ha}$ (19,271/acre)

1 and 23,800/ha (9,631/acre) respectively] were higher than normally recommended for standard field
2 production (Maynard and Hochmuth 1997) but corresponded with standard practices in more intensive
3 plasticulture production systems (Wells and Loy, 1985).

4 The low tunnels [1 m wide x 0.75 m tall (3.3 x 2.5 ft)] were constructed by applying the covering
5 material over metal hoops. Clear perforated polyethylene [2 mil (0.051 mm, 0.002 inch), Western
6 Concorde Mfg, Calgary, Alta.] was used to cover the melons, while spunbond polyester [Reemay,
7 Reemay Inc., Old Hickory, Tenn.] was used on the peppers and tomatoes. The specific row covering was
8 selected for each crop based on previous research under Saskatchewan growing conditions (Waterer, 1992,
9 1993). The low tunnels were installed immediately after transplanting and were left in place until the
10 crops began to flower or they had fully utilized the available growing space within the tunnels.

11 Depending on the year and the crop, the crops in the low tunnels treatments were covered for 4 to 6 weeks.

12
13 The high tunnels [Ledgewood Farm Greenhouse, Moultonboro, N.H.] were 4.3 m wide, 2.5 m
14 high and 29 m long. The tunnels were covered with a single layer of 6 mil (0.153 mm, 0.006 inch)
15 polyethylene [Ledgewood Farm Greenhouse, Moultonboro, N.H.]. Endwalls were also constructed of
16 polyethylene.

17 Air temperatures at 30 cm (0.98 ft) were monitored at two points inside both the high and low
18 tunnels and in the open. In the first year of the trial, the sides of the high tunnel were raised whenever
19 temperatures inside the tunnel exceeded 35 °C (95.0 °F). In subsequent years, the high tunnels were kept
20 closed, irrespective of the temperature, until the onset of flowering. From flowering onwards, the high
21 tunnels were managed to maintain temperatures below 40 °C (104.0 °F). No attempt was made to
22 regulate the temperature inside the low tunnels.

23 Honeybee hives were placed in the immediate vicinity of the test plot. In 2000, small colonies
24 were also placed inside the high tunnels. The plots were irrigated whenever soil moisture potentials in the
25 root zone fell below -40 kPa (-0.40 bars). At 6 and 12 weeks after transplanting 20 kg ha⁻¹ (17.8 lb/acre)

1 N as 46N-0P-0K was applied through the drip irrigation system. The crops were evaluated weekly for
2 insect or disease problems.

3 The melon and tomato crops were harvested twice weekly once the fruit reached maturity. The
4 muskmelons were harvested at full slip and the tomatoes at the breaker stage. The peppers were once-over
5 harvested just prior to the first killing frost. Fruits were counted, weighed, and graded based on Canadian
6 Food Inspection Agency market standards (Canadian Food Inspection Agency, 2002) for acceptable size,
7 shape, and freedom from defects. Peppers which had begun to mature to red were segregated from the
8 green fruit, as red fruit command a substantial price premium. The crop residues were removed from the
9 high tunnels in the fall and the sides of the tunnels were rolled up to expose the interior to winter
10 conditions. The low tunnels were moved each year, but the high tunnel remained at its original site.

11 **Data analysis.** Each crop was analyzed separately. All yield data were converted to yield per
12 unit length of row. Cultivar yields were pooled and averaged in crops where multiple cultivars were tested
13 in a given year. Standard analysis of variance procedures were used, with site-years considered as
14 replicates, followed by t-tests for comparisons of treatment means. In the tomato and melon crops,
15 weekly fruit yields until the first killing frost were used to calculate the time after transplanting required
16 for 50% of the fruit to mature (T-50). Gross returns were based on in-season wholesale prices for the
17 various crops (F.O.B. Saskatoon, Canada in \$ 1 U.S = \$ 1.66 CDN). Gross returns for the pepper crop
18 factored in the price premium paid for red fruit. The cost per unit production area of the two tunnel
19 systems was calculated by dividing the cost of materials and installation by the corresponding amount of
20 usable cropping space. The relative cost efficiency of the two tunnel systems was calculated by comparing
21 gross returns/unit production area as a function of the cost of the materials and labor required to install and
22 maintain the tunnels.

23 24 **Results and discussion**

25

1 **High tunnel observations.** The high tunnels were easily erected with minimal construction skills
2 or equipment. After three growing seasons, the high tunnels were still structurally sound, but the 6-mil
3 polyethylene covers had to be replaced due to tears and yellowing.

4 The 1998 growing season was considerably warmer than 1999 or 2000. Cumulative growing
5 degree days (GDD) [base 10 °C (50.0 °F)] in the open and inside the two types of tunnel from the time of
6 planting until the low tunnels were removed and from the time of planting until the first fall frost during
7 the three cropping seasons at the Saskatoon site are presented in Table 1. Low tunnels constructed of
8 perforated polyethylene accumulated GDD more rapidly than the more porous nonwoven polyester. The
9 relative rate of accumulation of GDD in the high tunnels varied among years. In 1998, the non-ventilated
10 low tunnels constructed of clear polyethylene accumulated GDD more rapidly than the high tunnels which
11 were ventilated once temperatures exceeded 35 °C. As early crop growth in the low tunnels was superior
12 to growth in the ventilated high tunnels in 1998, in subsequent years the high tunnels were kept closed
13 early in the season, irrespective of the temperature. In 1999, cumulative GDD in the high tunnels, both
14 early in the season and accumulated over the entire season, were substantially higher than in the low tunnel
15 treatments. Cloudier than normal weather during 2000 kept temperatures in the high tunnels relatively
16 low.

17 Although temperatures in both types of high tunnels often exceeded the published optima for the
18 test crops (Kinet and Peet, 1997; Maynard and Hochmuth, 1997; Wien, 1997) there were few indications
19 of heat stress. Gent (1992) found that delaying ventilation of high tunnels until temperatures exceeded 38
20 °C (100.4 °F) accelerated vegetative growth of tomatoes and promoted early fruiting relative to ventilation
21 at lower temperatures. However, maintaining the tomato plants under these conditions eventually resulted
22 in nutrient deficiencies and reduced total fruit yields. By contrast, the tomato and muskmelon crops in the
23 high tunnels in this study appeared healthier than the crop in the open field through the warmest days of
24 the summer. Once fruiting began, the pepper plants in the high tunnel were less vigorous than the plants
25 grown in the open field. This loss of vigor may have been related to heat stress, but it may also reflect the

1 metabolic load exerted by the larger and more rapidly developing fruit crop in the high tunnels. When
2 several crops are grown simultaneously in a high tunnel, conditions must be managed to maximize overall
3 productivity. As the optimum temperature for pepper plants is lower than for tomatoes and muskmelons
4 (Maynard and Hochmuth, 1997; Wien, 1997), health of the pepper crop may have been compromised for
5 the sake of the two other crops. Dedicating entire high tunnels to a single crop would simplify
6 temperature management.

7 The high tunnels provided only about 2 °C (3.6 °F) protection from spring or fall frosts (data not
8 shown). This is comparable to the degree of protection provided by standard low tunnels (Waterer, 1992).
9 The frost protection provided by the high tunnels extended the fall harvest period by an average of two
10 weeks but the impact on yield was minimal as low temperatures slowed crop development well in advance
11 of the first killing frost.

12 Weed populations between the mulch rows were lower inside the high tunnels than outside. The
13 area between the rows in the high tunnel never received rainfall, while in the standard management regime
14 weeds germinated between the rows following each rain event. All weeds were controlled by mechanical
15 tillage and did not compete with the crop. Over the three cropping seasons there were few problems with
16 disease or insect pests in either of the tunnel treatments and no pesticides were required. The short, cool
17 and dry growing season typical of the Canadian prairies appeared to prevent the problems with insects and
18 foliar disease noted when high tunnels are used in warmer and more humid regions (Wells and Loy,
19 1993).

20 The cost of materials, installation, and maintenance for the high tunnels over the 3-year test period
21 was \$US 1990. This corresponds to a cost of \$ 13.25/m (\$ 4.04) of usable row space based on three rows
22 spaced 1.4 m (4.59 ft) apart running the length of the high tunnel. The corresponding cost for the standard
23 spun bonded polyester or perforated polyethylene low tunnels was \$ 0.46/m (\$ 0.14/ft).

24 **Muskmelon.** The first fruits matured 2 to 3 weeks earlier in the high tunnel than in the standard
25 low tunnel treatments. Similarly, the T-50 in the high tunnels was two weeks earlier than in the standard

1 regime (Table 2). In the unusually warm 1998 growing season, differences in marketable yields with the
2 two types of tunnel were minimal. By contrast, in the much cooler 2000 growing season, excellent yields
3 were obtained with the high tunnels, while no fruits matured prior to the first fall frost in the low tunnel
4 plots. Averaged over the three test seasons and two sites, total yields of mature fruits were 59% higher
5 with the high tunnel than with the low tunnel treatment (Table 2). A far greater proportion of the fruits set
6 in the high tunnels matured prior to frost than when standard low tunnels were used (Table 2). Total
7 yields (mature and immature fruit) were similar with the two production systems. Fruits grown inside the
8 high tunnel were larger than fruits in the standard management regime (Table 2) while the flavor and sugar
9 contents were not influenced by the tunnel type (data not shown). Hochmuth et al. (1998) noted that
10 producing melons in high tunnels in Florida reduced grade-out due to fruit cracking relative to low tunnel.
11 The cooler temperatures and limited rainfall characteristic of the Canadian prairies minimized problems
12 with fruit cracking in this trial.

13 Vigor of the muskmelon crops in the high tunnel declined rapidly during August and few fruits
14 were harvested through the last 30 d of the growing season. The decline in crop vigor coincided with the
15 main fruit harvest. The stress placed on the plants by the heavy crop of developing fruit may have
16 weakened the plants. The muskmelon cultivar Earligold was selected for its high yields in field trials
17 conducted under the limited growing season available in Saskatchewan (Waterer and Bantle, 1998).
18 Cultivars adapted to longer growing seasons may have a higher overall yield potential in the high tunnels.
19 Sequential planting would also extend the potential harvest period in the high tunnel. Trampling damage
20 to the vines during harvest within the confined space of the high tunnels may have contributed to the
21 observed decline in crop vigor. Staking could potentially alleviate this problem. Staking may also
22 accelerate fruit maturity but it is labor intensive and the handling required may cause plant and fruit
23 damage.

24 **Tomato.** The crop flowered and the first fruits matured 2 to 3 weeks earlier inside the high tunnel
25 than in the low tunnel regime. However, the time required for 50% of the fruit to mature was only about a

1 week different for the two tunnel types (Table 2). Averaged over the three test seasons, total yields of
2 mature marketable tomato fruits were 47% greater with the high tunnel than with the low tunnels (Table
3 2). A higher proportion of the fruits in the high tunnels matured prior to frost than in the low tunnel plots
4 (Table 2), but a significant portion of the potential crop was still lost to fall frost in the high tunnel. Total
5 yields (mature + immature) were comparable for the two production systems. Average fruit size (Table 2)
6 and taste were also comparable in the two production systems. The semi-determinant cultivars selected
7 for testing thrived in the high tunnel environment. Fruit set in the high tunnels was excellent in spite of the
8 supra-optimal air temperatures (Kinet and Peet, 1997), limited air movement, and the tendency of
9 honeybees to avoid tomato flowers. Fruit quality was excellent in both production systems. The
10 incidence of blossom-end rot was lower inside the high tunnel than outside, but this was balanced by
11 slightly higher grade-out due to bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*) in the high tunnel
12 (data not shown). Higher humidities within the confines of the high tunnels could have contributed to the
13 observed reduction in blossom-end rot (Tartier, 1994) and the increased incidence of bacterial disease
14 (Tartier and Pitblado, 1994).

15 **Pepper.** Averaged over the three site-years, yields of mature fruit were 59% greater with the
16 high tunnel than with the standard low tunnels (Table 2). More than 10 times as many fruits in the high
17 tunnels had begun to change color to red than with the standard regime (Table 2). Average fruit size
18 (Table 2) and quality were comparable in the high and standard tunnel treatments. As previously noted,
19 vigor of the pepper crop in the high tunnel declined as season progressed. Whether this loss of vigor
20 could be avoided by more careful maintenance of air temperatures or through greater attention to fertility
21 or other inputs merits further attention.

22 **Economic analysis.** Gross returns based on in-season wholesale prices (F.O.B. Saskatoon,
23 Canada, in \$US) for the high tunnel and standard low tunnel cropping systems averaged over the 1998-
24 2000 cropping seasons are presented in Table 3. The high tunnels consistently produced a higher gross
25 return/unit row length than did the standard production practices. However, the material costs for the high

1 tunnels (\$13.25/m of row) far exceeded the cost of the standard low tunnels (\$ 0.46/m of row).
2 Depending on the crop, it would take from 2 to 5 growing seasons before the increase in gross returns
3 provided by the high tunnels exceeded their higher capital costs (Table 3). The most economically
4 attractive cropping option in the high tunnels was peppers, primarily because of the superior yields of
5 mature red fruit which commanded a price premium.

6 7 **Conclusions**

8 The three years of trials demonstrated that high tunnels have the potential to accelerate growth and
9 improve yields of several warm-season vegetable crops relative to standard low tunnels, although the
10 benefits obtained varied with the crop and the growing season. The high tunnels were most beneficial
11 during cool growing seasons particularly if the tunnels were managed with the objective of maintaining
12 relatively high air temperatures through the vegetative stage of crop development. The crops grown inside
13 the high tunnels were of good quality with no unusual disease or insect problems. Material and
14 construction costs of the high tunnels were substantially higher than standard low tunnel option.
15 Cost/benefit analyses suggests that the high tunnels required a multi-year payback period when used to
16 generate product for sale into wholesale markets.

17 Some options to improve the cost efficiency of using high tunnels include; 1) reduced capital
18 costs through volume purchases of construction materials and use of more efficient construction methods,
19 2) increase yields / unit area should be possible through the use of better varieties, closer between- and
20 within-row spacings (Lamont et al., 2001; Loncaric et al., 1999), staking, relay cropping, and use of other
21 agronomic practices tailored to high intensity production, 3) growing higher-value crops. The potential
22 benefits of using the high tunnel vary with both the crop and the market. Growers need to select crops that
23 benefit from the high tunnel environment in terms of accelerated maturity, enhanced yields, or improved
24 quality. Although tomatoes, peppers, and melons are high-value crops, which clearly benefit from the
25 high tunnel environment, greater profits may be available from other crops. Off-season production of

1 small fruits (raspberry and strawberry) as well as cut-flowers have been identified as potentially profitable
2 cropping options in high tunnels (Lamont et al., 2001; Wells and Loy, 1993). Produce available either
3 earlier or later than normal may command a price premium. Although the high tunnels accelerated crop
4 development, they provided little frost protection. This limited yields and reduced access to higher value
5 out-of-season markets. The addition of simple supplemental heating systems such as a propane burners
6 may be warranted. Finally, the earliness and high quality of crops grown in high tunnels may make them
7 better suited to marketing direct to the consumer rather than through the wholesale system.

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Table 1. Cumulative growing degree days [base 10 °C (50.0 °F)] for tunnel treatments from planting until removal of the low tunnels or for the entire growing season.

| | Early ^z | | | | Growing Season ^y | | | |
|---------|--------------------|------------|-------|-------------|-----------------------------|------------|-------|-------------|
| | Open | Low tunnel | | High tunnel | Open | Low tunnel | | High tunnel |
| Year | | Nonwoven | Clear | | | Nonwoven | Clear | |
| 1998 | 425 ^x | 720 | 835 | 810 | 1250 | 1545 | 1675 | 1925 |
| 1999 | 375 | 620 | 700 | 1000 | 1100 | 1355 | 1500 | 1900 |
| 2000 | 200 | 310 | 325 | 275 | 1150 | 1475 | 1400 | 1850 |
| Average | 333 | 550 | 620 | 695 | 1167 | 1458 | 1525 | 1891 |

^z From transplanting in late May until removal of the low tunnels in early July.

^y From transplanting in late May until the first killing frost.

^x 1 °C = 1.8 °F.

Table 2. Yield characteristics averaged over 3 years for muskmelon, tomato, and pepper grown using high or low tunnels.

| | T-50 (d)^z | Marketable yield (kg·m⁻¹ of row)^y | % mature^x | Fruit wt. (kg)^y |
|--------------|-----------------------------|--|-----------------------------|-----------------------------------|
| | Muskmelon | | | |
| High tunnel | 87 (80-92) ^w | 17.8 (8.7-32.0)* | 90 (79-98) | 1.34 (1.10-1.66) |
| Low tunnel | 101 (97-109) | 7.2 (0-24.3) | 40 (0-82) | 0.97 (0.59-1.48) |
| Significance | ** | ** | ** | ** |
| | Tomato | | | |
| High tunnel | 99 (97-101) | 12.7 (8.1-16.9) | 53 (39-57) | 0.14 (0.13-0.16) |
| Low tunnel | 107 (104-108) | 6.6 (3.5-11.7) | 33 (21-49) | 0.14 (0.13-0.15) |
| Significance | * | ** | ** | NS |
| | Pepper | | | |
| High tunnel | -- | 10.9 (9.0-13.2) | 70 (40-100) | 0.12 (0.11-0.13) |
| Low tunnel | -- | 4.5 (2.8-5.9) | 7 (0-14) | 0.13 (0.12-0.13) |
| Significance | -- | ** | ** | NS |

^z Time from transplanting until 50% of the fruits ripened.

^y 1.0 kg·m⁻¹ = 0.67 lb/ft, 1.0 kg = 2.20 lb. 1 kg·m⁻¹ of row = 7,200 kg·ha⁻¹ = 6,422 lb/acre.

^x (Yield prior to frost of mature fruit/total yield) x 100.

^w Values in brackets represent the range in means over site years. Melon n=6, tomato n=3, pepper n=3.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively, for tests of tunnel effects for each crop.

Table 3. Gross returns based on wholesale prices and the number of seasons before returns after material costs for the high tunnels exceed standard low tunnels.

| | | Price (\$/kg) ^z | (\$/m of row) | Seasons ^y |
|---------------|-------------|----------------------------|---------------|----------------------|
| Melon | High tunnel | 0.47 | 8.37 | 2.6 |
| | Low tunnel | | 3.38 | |
| Tomato | High tunnel | 0.49 | 6.22 | 4.3 |
| | Low tunnel | | 3.23 | |
| Pepper | High tunnel | Red - 1.15 | 10.89 | 1.6 |
| | Low tunnel | Green - 0.65 | 3.08 | |

^zWholesale prices F.O.B Saskatoon Canada in \$US for the fall marketing period averaged for 1998-2000.

\$ 1.00/kg = \$ 0.45/lb, \$ 1.00/m = \$ 0.30/ft.

^y Number of seasons required calculated as: (cost/m of high tunnels-cost/m of low tunnel)/(gross/m high tunnel-gross/m of low tunnel).

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