Research Reports

The Economics of Low-cost High Tunnels for Winter Vegetable Production in the Southwestern United States

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SUMMARY. Relatively little season extension research has been conducted in the southwestern United States, particularly with low-cost high tunnels or hoop houses for small-scale farmers. In this study, the economics of winter production of two leafy crops [lettuce (*Lactuca sativa*) and spinach (*Spinacia oleracea*)] in high tunnels in two locations in New Mexico were investigated, first using a simulation analysis in which yields were stochastic variables followed by a sensitivity analysis to examine returns from the high tunnel designs more closely. The returns examined in the sensitivity analysis were net of high tunnel materials, crop seed cost, and electricity. Two planting dates were tested and three high tunnel designs were examined: a single layer covering the house (SL), a double layer inflated with air (DL), and a double layer inflated with air and containing black water barrels to store heat (DL+B). The SL and DL designs appear to be the more appropriate technology for both locations for spinach, whereas for lettuce the DL+B model might be a reasonable option in Alcalde, a more-northern location. Overall, the SL and DL models provided adequate protection for growing crops, were less expensive to build, provided more interior growing space, and resulted in higher probabilities of producing positive returns, compared with the DL+B design. The DL design performed similarly to the SL design, but required running electricity to the structure to power the inflation fan, adding to the cost. As a result, expected returns in all cases were higher using the SL design based on the results of the sensitivity analyses. Combining the risk and the sensitivity analyses provides growers with a unique evaluation process to make high tunnel design, planting date, and crop choices.

Often called hoop houses, high tunnels are constructed by stretching a layer of polyethylene plastic over hoops of metal or polyvinyl chloride (PVC). Most high tunnels rely on passive ventilation through roll-up sides, large doors, or removable end walls. High tunnels are less-complex, less-expensive versions of a greenhouse because of passive heating and cooling and inexpensive glazing. They can offer growers a cost-effective way to extend the growing season for high-value crops such as fruits, vegetables, and cut flowers. High tunnels also allow small farmers to gain market share in the niche market of "locally grown" products at a time of the year when most fruits and vegetables are grown elsewhere.

Extending the vegetable production season without incurring prohibitive costs is an important goal of many farmers, especially small and beginning farmers with limited resources. Extending the season with high tunnels allows for a more-constant income flow and some control of the crop growth environment. High tunnels can provide protection against some insects, early freezes, hail, and other weather events. High tunnels can also facilitate better market planning. Season extension technologies alter the growing environment equivalent to moving three U.S. Department of Agriculture Plant Hardiness Zones to the south, which makes production of spinach and lettuce in cold winter weather possible (Coleman, 2009; Wells and Loy, 1993).

Although high tunnels have been extensively studied in the eastern and midwestern parts of the United States, little work has focused on the southwestern part of the country. With limited water and a dry climate, farmers in the southwestern United States are under pressure to divert agricultural land and water to residential and other nonagricultural uses (Hurd and Coonrod, 2008). At the same time, new marketing opportunities are developing that encourage schools and other public institutions to purchase fresh produce from local farmers. To take advantage of these opportunities and deal with these challenges, farmers need to be able to supply fresh produce in a cost-effective manner during the late fall, winter, and early spring months. In most of the southwestern United States, the majority of winter days are sunny, but nights (and in some areas, days) are below freezing. Low-cost, passive-solar high tunnels seem to be an ideal fit for farmers in this region. In recent years, New Mexico agricultural producers have adopted high tunnel technology, but detailed production and economics data are lacking. Stakeholders need additional information about winter vegetable production in high tunnels.

High tunnels are generally tall enough to walk in, whereas low tunnels are designed to cover the crop itself and are typically 1 to 2 ft tall. Low tunnel technology has been explored as one form of extending the crop season in southern New Mexico. Ma (2009) examined the economic impact of using low tunnels to extend the season for four lettuce and four spinach cultivars. For lettuce, low tunnels improved yields as much as 23% in the fall, whereas, in the spring, those improvements were as high as 70% when compared with the control. Spinach also performed well, with yields 68% higher in the fall and 66% higher in the spring when compared with the control (Ma, 2009). A partial budget analysis was used to evaluate the economic performance of the low tunnels. A price of \$4/lb was used, based on previous sales of lettuce and spinach in the area. In Fall 2008, rowcovers had a positive economic effect on only one cultivar of lettuce, with a cumulative impact of \$1170/acre over three harvests. All other lettuce and spinach cultivars in the fall had a negative economic effect under rowcovers. In the spring, rowcovers had positive economic effects on all lettuce and spinach cultivars, with the highest cumulative returns from three harvests of \$36,388/acre for one lettuce cultivar. A spinach cultivar had the highest returns of \$46,123/acre from four harvests. However, high tunnels have increasingly been adopted in New Mexico due to the labor involved in managing and maintaining low tunnels.

In the northern parts of the United States and Canada, high tunnels present several advantages, such as allowing the crop to be planted as much as a month earlier and protecting against rain and wind, resulting in a higher quality product (Wien, 2009). Growers surveyed in Missouri, Kansas, Nebraska, and Iowa reported extending their season to 9 months of the year using high tunnels and 91% reported growing tomatoes (*Solanum lycopersicum*) in high tunnels (Knewtson et al., 2010). Other crops reported were lettuce, spinach, leafy greens, cucumbers (*Cucumis sativus*), and peppers (*Capsicum* sp.). Internationally, the most commonly produced crop in high tunnels is tomato, followed by pepper, cucumber, muskmelon (*Cucumis melo* var. *reticulatus*), and lettuce (Knewtson et al., 2010).

In Michigan, nine case studies were used to analyze the viability of high tunnel vegetable production (Conner et al., 2010). The materials cost roughly \$10,000 for a tunnel of ≈2800 ft^2 (Conner et al., 2010). Net payback was an estimated 4.2 years, assuming the entire net mean monthly income of \$201 was used to pay for the investment (Conner et al., 2010). Waterer (2003) evaluated the economics of summer vegetable production in high tunnels and low tunnels in Canada. Crops in high tunnels matured earlier and produced higher yields before a killing frost, but did not effectively extend the growing season. High tunnels required much higher initial investment, but enhanced gross returns on the wholesale market allowed for a 2- to 5-year payback period. Economics information is available for other parts of the United States and Canada but is limited for growers in the southwestern United States.

Risk and uncertainty are part of any business, including agricultural investments. Although capital investment costs may be easy to estimate, yields and prices received in the market are variables over which farmers have limited control. These variables can greatly influence the decisions of small growers who have constrained budgets. Developing a model, that takes risk into account, is important to improve investment decisions. Therefore, it is also important for vegetable growers to understand their probabilities of covering material and seed costs before investing.

@Risk™ statistical software (Palisade Corp., Ithaca, NY) has been widely used to make financial decisions by examining uncertainty. The software has been used in the financial industry for retirement planning, currency valuation, portfolio optimization, and discounted cash flow analysis (Togo, 2004). It is used in the insurance industry in estimating loss reserves. @Risk™ is also used in the energy industry to determine oil reserves estimation, exploration, and production. Yeboah et al. (2012) used @Risk™ to examine the economic feasibility of a North Carolina biodiesel plant that used canola (*Brassica rapa*) seeds as the primary feedstock. The software has also been used in agricultural investment decision projects (Tzouramani and Mattas, 2004). BestFit is a feature of @Risk™ that identifies the distribution that best fits the input data (Jankauskas and McLafferty, 1996). In combination with simulation software, these distributions can be used to define uncertainty in the model.

This project evaluated three models of high tunnels for winter production of leafy greens over three seasons. The emphasis was on low-cost, practical structures that are applicable to farmers with limited resources and who may wish to test winter production before making larger investments in more advanced greenhouse

Use of trade or product names does not imply endorsement of the products named nor criticism of similar ones not named.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
0.0283	ft^3	m^3	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha^{-1}	0.8922
0.0254	mil	Mm	39.3701
1.6093	mile(s)	km	0.6214
33.9057	oz/yard^2	g·m^{-2}	0.0295
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

technology or transitioning to larger units. Specific objectives were to 1) quantify the differences between three passive solar high tunnel designs of different expense and heat-retention capacities, 2) evaluate growth and yield of one spinach cultivar (Long Standing Bloomsdale) and one lettuce cultivar (Flashy Trout's Back) at two planting dates within each tunnel, and 3) conduct economic analyses using novel software to develop a risk model to determine relative probability of profitability of each tunnel design.

Materials and methods

High tunnel design, establishment, and management. Field research was carried out at two branch research stations of New Mexico State University (NMSU) over 3 years (2009–12). At both NMSU-Alcalde (northern location) and NMSU-Las Cruces (southern location), the following tunnel designs were constructed: single layer of woven polyethylene plastic for tunnel exterior (SL); double layer of woven polyethylene plastic for tunnel exterior (DL); and double layer of woven polyethylene plastic for tunnel exterior, plus sixteen 55-gal black metal barrels filled with water (DL+B), the latter to potentially increase heat retention.

The frames of the houses were constructed from 2 × 4-inch and 4 × 4-inch raw (i.e., not pressure treated) lumber and bent 2-inch PVC pipe (Fig. 1). Tunnels were oriented with the length running east to west to maximize interception of solar radiation. A DL design tunnel was also constructed at a farmer collaborator site ≈5 miles west of Las Cruces. Since rowcover typically increases temperatures from 2 to 3 °C (Wells and Loy, 1993), spunbonded polypropylene floating rowcovers [85% light transmission, 0.55 oz/yard^2 (Agribon AG-19; J&M Industries, Ponchatoula, LA)] were used inside the tunnels to provide extra protection for all crop treatments at both research stations and the on-farm site. Lettuce and spinach were planted in separate plots 24–25 Nov. and 15–17 Dec. at all locations in year 1. In years 2 and 3, planting dates were changed to 27–29 Oct. and 17–19 Nov. In year 3, low germination caused by salt accumulation was noted in Las Cruces for both planting dates, with the October planting being more severely affected. This forced a replanting of the October plots in early January. Germination tests revealed that the seeds had low vigor, which combined with the high salt levels, affected growth in the Las Cruces houses in year 3. The salinity problem was not encountered at Alcalde.

Plots were hand-seeded and manually weeded as needed. Within each tunnel, individual plots were 2 × 5 ft with an 8-inch buffer between plots. Within plots, three rows (north-south orientation) of each crop were planted 8 inches apart. Standard yield (fresh weight of marketable product) data were collected. The first harvest was attempted 28 d after planting (DAP) for lettuce and 40 DAP for spinach (recommended first harvest intervals), but varied by location. Subsequent harvests occurred every 3 weeks in Las Cruces and every 4 weeks in Alcalde. Both lettuce and spinach were grown as "cut and come again" rather than for heads.

Fig. 1. Orientation and structure of high tunnels at the New Mexico State University Sustainable Agriculture Science Center in Alcalde, NM. The long side of the structure runs east to west to maximize solar radiation interception during the winter months.

Fertilization and pest issues were managed using organic principles and amendments. Aphids (*Aphis* sp.) observed on spinach were treated using a premixed insecticidal organic soap (Safer Brand; Woodstream Corp. Lititz, PA) according to the manufacturer's recommendations. At Alcalde, irrigation water was applied through a drip system in year 1 and a self-draining overhead sprinkler system in years 2 and 3 to avoid freezing of the lines observed in the first season. In Las Cruces, overhead sprinkling and hand watering were used to irrigate depending upon weather conditions. In both locations, soil was kept evenly moist at all times during the project. Because the overhead sprinkling system in Las Cruces led to soil salinity increases, irrigation using watering cans was needed to help leach the salts below the root zones and improve growing conditions. During the summer months, cowpea (*Vigna unguiculata* 'Iron and Clay') seeds were planted in the hoop houses at a rate of 100 lb/acre as a rotational cover crop. In Las Cruces, the cover crop and associated biomass were incorporated into the soil ≈1 month before planting lettuce and spinach. In Alcalde, cowpea was incorporated ≈3 weeks before the first planting date in 2010 and 7 weeks prior in 2011. Cowpea was expected to deliver ≈100–120 lb/acre (Wang and Nolte, 2010).

Materials costs along with maintenance cost data were recorded for each on-station tunnel design. Small farmers in New Mexico, especially new farmers, typically do not hire labor outside the family. Thus, labor costs were excluded so that an individual farmer can determine if their time and effort is justified by the expected gross returns for the 4-month period in these structures. Labor was not considered a variable cost since identical crops and crop management were applied to all tunnel designs. Thus, the economic analysis compared the economic performance of the different high tunnel designs based on the costs, yields, and the probability that the returns of each high tunnel design would match or exceed structural and maintenance costs.

Experimental design. At Alcalde and Las Cruces, the three tunnel designs were replicated twice for a total of six tunnels at each location. Tunnels were arranged in a completely randomized design at Alcalde since soil in the experimental field was homogeneous, and a randomized complete block design (RCBD) at Las Cruces due to likely soil textural differences. The experiment was carried out over three winter seasons (2009–12). The plastic covering the high tunnels varied according to the design of the high tunnel. The first (interior) layer of the DL and DL+B designs was 8-mil woven plastic (SOLAROOF 140, J&M Industries). The second (outer) layer of plastic was thicker at ≈11-mil (SOLAROOF 172, J&M Industries). The SL design had a single layer of SOLAROOF 172.

In the first season, the DL and DL+B were not completed in Las Cruces. As a result, the two houses that were intended to be SL designs were covered by the thicker SOLAROOF 172 plastic and the four intended to be DL and DL+B houses only had the thinner SOLAROOF 140 interior plastic, but not the second exterior layer. At the Alcalde research station, all three designs were completed from the start of the project.

In Las Cruces, the DL and DL+B production data could be collected only in the second (2010–11) season. As previously noted, third-season data were compromised due to germination and salinity problems. However, a Las Cruces-based cooperator had a single DL hoop house from which 3 years of data were collected from replicated plots of spinach and lettuce. Data from the Las Cruces' cooperator site were also analyzed because the experiment, harvests, and data were handled in the same way, by the same staff, and on the same dates as at the research station; the Las Cruces station had only year 2 experimental data. In addition, the DL high tunnel at the cooperator site was completed in year 1 and had a complete data set (3 years of harvests). In year 1, lettuce and spinach were planted in November and December. In years 2 and 3, lettuce and spinach were planted in October and November.

A 2-ft walking path was created down the center of each tunnel (Fig. 2). A generalized split-plot design with repeated measures was followed at each of the two research locations. Within a tunnel, six replications of the four-level treatment factor defined by planting date (November and December or October and November) and crop (lettuce and spinach) were laid out in a RCBD. The cooperator site had four replications. Each year, the plots were rerandomized and years and sites were analyzed separately due to seasonal variation (Enfield, 2012). In the DL+B design, 16 barrels were placed on the north side of the high tunnel. In the SL and DL designs, the equivalent space taken by the barrels in the DL+B houses remained empty. However, this space was accounted for in the economic analysis. The DL and DL+B designs were inflated with a mechanical blower [148 ft^3/min (FarmTek, Dyersville, IA)] to provide extra insulation and protection against colder temperatures. Electric lines were run to these tunnels to power the fans.

HARVESTS AND DATA COLLECTION. To harvest, plants were cut ≈1 inch above the soil surface to allow for repeated harvests or "cut and come again." Data were collected from the center 3 ft of the middle row in each plot to avoid edge effects. The rest of the plot was also harvested separately (data not presented). During the first season, there were two harvests in Alcalde and three harvests in Las Cruces. In the second season, the planting dates were earlier, which increased the number of harvests: Alcalde had three harvests, whereas Las Cruces had five both at the research station and cooperator site.

Crops that were considered too small to be marketable (i.e., less than 1 inch) were not harvested, and their fresh weight was recorded as zero. When there was no germination in the center 3 ft of the plot, the fresh weight was also recorded as zero. Crops were harvested and yields recorded until the quality diminished based on taste, appearance, and regrowth of the crops (Table 1). After several harvests, lettuce developed a bitter flavor, and spinach began to bolt. Other data recorded included dry weight, plant count, average plant height, and temperature probe data. These data and the fresh yields were analyzed in a separate research project (Enfield, 2012).

ECONOMIC ANALYSIS. The research plots were laid out perpendicular to the length of the house to accommodate the replication of each crop and planting date combination, but this layout would likely not be used for market production. Market farmers more likely would plant lengthwise to approximate a small push planter pattern, leaving a 2-ft walkway down the center of the tunnel (Fig. 2). To calculate planting space for such a layout, exact measurements of the inside of the structure were taken: the DL+B model measured 30.25 × 13.5 ft due to the space occupied by the barrels and the remaining models measured 30.33 × 16.33 ft. Yield per plot came from an area that measured 2 ft^2 (8 inches × 3 ft). These measures resulted in a yield factor of 217.3 for the SL and DL designs and 174.4 for the DL+B design. The SL and DL yield factor calculations were as follows: (16.33 ft – 2 ft) × 30.33 ft = 434.63 ft^2/2 ft^2 = 217.3. The DL+B calculation was (13.5 ft – 2 ft) × 30.33 ft = 348.80 ft^2/2 ft^2 = 174.4. The plot yield from each scenario (i.e., the combination of each high tunnel design, planting date, and crop) was multiplied by the yield factor, resulting in the estimated total high tunnel yield expected in commercial production per square foot.

Local small-scale growers with a high tunnel of the size studied in this project would likely sell in either farmers' markets or local retail outlets. Prices ($2 to $6 per pound) were obtained during the harvest season from Mountain View Cooperative, a retail outlet in Las Cruces and from La Montanita Co-op, a

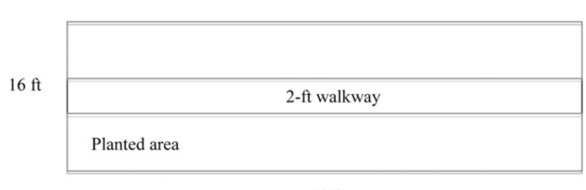

Fig. 2. High tunnel dimensions and planting design assumptions for market production and economic analysis in New Mexico (single-layer and double-layer designs only). Interior dimensions were ≈16 × 30 ft; 1 ft = 0.3048 m.

Table 1. Yields of winter leafy greens in three high tunnel designs in two New Mexico locations, three planting dates, and three seasons (2009–12).

			Location, season[y]			
			Las Cruces, S2	Alcalde, S1	Alcalde, S2	Alcalde, S3
Design[z]	Planting mo.	Crop	Mean yield (lb/tunnel)[x]			
SL	October	Lettuce	51.7	N/P[w]	36.1	60.9
SL	November	Lettuce	39.4	8.9	38.3	42.2
SL	December	Lettuce	N/P	7.1	N/P	N/P
SL	October	Spinach	47.6	N/P	28.5	49.7
SL	November	Spinach	47.5	6.6	14.4	37.0
SL	December	Spinach	N/P	6.4	N/P	N/P
DL	October	Lettuce	52.4	N/P	37.3	90.8
DL	November	Lettuce	55.5	11.1	18.5	76.7
DL	December	Lettuce	N/P	10.1	N/P	N/P
DL	October	Spinach	47.4	N/P	36.8	67.3
DL	November	Spinach	48.3	12.7	24.5	52.2
DL	December	Spinach	N/P	10.5	N/P	N/P
DL+B	October	Lettuce	42.3	N/P	38.7	68.2
DL+B	November	Lettuce	13.2	14.8	45.9	48.0
DL+B	December	Lettuce	N/P	7.8	N/P	N/P
DL+B	October	Spinach	31.7	N/P	23.8	40.0
DL+B	November	Spinach	38.0	13.5	12.4	39.2
DL+B	December	Spinach	N/P	9.0	N/P	N/P

[z]SL = single layer of plastic, DL = double layer, DL+B = double layer plus barrels.
[y]S1 = season 1 (2009–10), S2 = season 2 (2010–11), S3 = season 3 (2011–12).
[x]High tunnels were 16×32 ft (4.9×9.8 m) outside dimensions; 1 lb/512-ft^2 (47.6 m^2) tunnel = 85.0781 lb/acre = 95.3599 kg·ha^{-1}.
[w]Not planted in seasons 2 or 3.

locally owned chain of four retail food cooperatives headquartered in Albuquerque, NM.

Costs for each model structure were depreciated using straight-line depreciation for 10 years in conformity with the Internal Revenue Service's Farmer's Tax Guide, which states that horticultural structures have a 10-year recovery period (under the General Depreciation System) (Internal Revenue Service, 2011). The annual depreciation cost was also divided by three to represent the 4-month winter season that this study examined. This step was important to accurately evaluate costs and revenues for the winter production period.

Maintenance costs were estimated by adding repair costs at each site and dividing by the number of high tunnels at each site, deriving an average maintenance cost per tunnel, which was added to the structural cost in the model. These maintenance costs primarily consisted of adding an extra layer of plastic to the end walls after initial construction. Fan replacement costs were not included in the DL and DL+B designs because the replacements typically were needed after 3 years. The materials to build each high tunnel varied according to their design. The SL tunnel material costs were $1029, the DL material costs were $1448, and the DL+B material costs were an estimated $1824.

Table 2. Example of yield distribution fits assigned by @Risk™ statistical software (Palisade Corporation, Ithaca, NY) for each high tunnel design, crop, and planting date scenario, Las Cruces, NM.

Scenario (tunnel design, crop, planting mo.)[z]	Distribution	Parameters
DL+B, L, November	Exponential	0.077027, Riskshift(–0.020818)
DL+B, S, November	Pearson	80.797, 80.431
DL+B, L, October	Logistic	0.232609, 0.096517
DL+B, S, October	Weibull	1.7021, 0.18557, Riskshift(0.11983)
DL, L, November	Logistic	0.232609, 0.096517
DL, S, November	Weibull	1.7024, 0.18557, Riskshift(–0.24029)
DL, L, October	Normal	0.2393, 0.14127
DL, S, October	Invgauss	0.22672, 1.07292, Riskshift(–0.010128)
SL, L, November	Exponential	0.18, Riskshift(-0.048649)
SL, S, November	BetaGeneral	1.5211, 2.9708, 0.0074485
SL, L, October	Normal	0.23612, 0.15632
SL, S, October	LogLogistic	–0.015838, 0.19868, 3.3955

[z]SL= single layer of plastic, DL = double layer, DL+B = double layer plus barrels, L = lettuce, S = spinach.

Using BestFit (a feature of @Risk software, 2010), a distribution was fit to the yield data (Table 1) of each scenario. The length of the data series varied, depending on how many seasons of data were available at each site, for each planting date and house design. The statistical distributions were truncated at zero on the lower bound, since negative yields cannot be obtained. To select a distribution, three goodness-of-fit tests were examined: chi-square, Kolmogorov–Smirnov, and Anderson–Darling tests. The Kolmogorov–Smirnov test was used to select the best fitting distribution for each scenario because this test detects discrepancies in the distribution tails more accurately than the chi-square and Anderson–Darling tests (Palisade Corporation, 2010). Example distribution fits for Las Cruces scenarios are shown in Table 2 to demonstrate the diversity of distributions and parameters. Revenue was estimated by multiplying the distribution of yields by a price simulation table that included a range of prices that were observed in local markets in Las Cruces and Albuquerque, NM, as well as Durango, CO, as described earlier.

Sensitivity analyses were conducted to estimate gross returns to growers given a range of prices and yields that encompassed the prices and yields relevant to the SL and DL tunnel designs and two crops. These two particular designs were studied more closely after the simulation analysis results indicated they were likely the two most viable tunnel design options. The returns estimated were generated using the "What-If Analysis" in a spreadsheet program (Excel; Microsoft Corp, Redmond, WA). Gross returns were estimated as the difference between gross revenues (yield × price) and the material costs of building and maintaining the structures, using 2010 local cost estimates. In addition, seed costs were included since they differed by cultivar, and for the DL and DL+B designs, electricity costs of running the fans were included. No other operational or investment costs were included in the sensitivity analyses since they did not vary by tunnel design or cultivar. Electric rates and inflation system blower usage records in Alcalde revealed a range of \$10 to \$35 for the 4-month study period, which was ≈1% of the total construction costs of the DL or DL+B designs. An estimate of \$15/tunnel for the production season was used in the sensitivity analyses for the DL design and DL+B designs, although only the analysis for the DL design is presented.

Results and discussion

SIMULATION RESULTS: LAS CRUCES. The simulation results showed, for each scenario and various prices, the probability that the difference between gross revenues, and structure and seed costs, exceed zero. In other words, the probabilities are estimates of the chance that structure and seed costs are covered by revenues at various prices (Table 3). Scenarios correspond to each crop (spinach or lettuce), planting date (October or November), and design (SL, DL, DL+B) combination.

In the case of spinach grown in Las Cruces, at the \$2.00/lb selling price level, the October planting in the SL design and the DL design had probabilities of 89% and 84% of having positive returns, respectively, compared with a 40% probability of positive returns in the DL+B design at the same price level and planting date (Table 3). As prices continue to increase, however, the probabilities grow closer between the scenarios, indicating the need for higher prices to cover the costs of the most expensive alternative. The higher yields of spinach planted in October in the SL design (47.6 lb) and DL design (47.4 lb), compared with the DL+B design (31.7 lb), in addition to the different structure costs, account for these results. October-planted lettuce results were similar, with the DL+B design probability of a positive return much lower (56%) than either the SL (79%) or DL (83%) designs (Table 3).

When the planting dates are compared at the \$2.00/lb selling price level for spinach, the percentage chance of earning a positive return was greater in October than November in both the SL (89% vs. 85%, respectively) and DL (84% vs. 71%, respectively) designs, but not in the DL+B design (40% vs. 55%, respectively). For both spinach planting dates in the DL+B design, the probabilities of a positive return at low prices would likely be unacceptable to a risk-averse grower. At \$5.00/lb, the probability of positive returns exceeds 80% for all spinach scenarios in Las Cruces, emphasizing again the need for higher prices to justify the investment in the DL+B design. Similar to spinach, the probabilities of positive

Table 3. Percentage chance of positive returns at different crop selling prices and in various high tunnel scenarios, Las Cruces, NM.[z]

Scenario (tunnel design, crop, planting mo.)[y]	Chance of positive returns (%)						
	Sale price (\$/lb)[x]						
	1.00	2.00	3.00	4.00	5.00	6.00	7.00
SL, L, October	54	79	88	92	94	96	97
SL, L, November	36	60	72	78	82	85	87
SL, S, October	50	89	97	99	99	100	100
SL, S, November	54	85	93	96	98	99	99
DL, L, October	45	83	93	96	98	99	99
DL, L, November	45	83	93	97	98	99	99
DL, S, October	28	84	96	99	99	100	100
DL, S, November	42	71	81	85	88	90	92
DL+B, L, October	25	56	69	76	81	84	86
DL+B, L, November	1	9	19	29	37	44	49
DL+B, S, October	3	40	63	76	84	89	92
DL+B, S, November	9	55	73	81	86	89	91

[z]Probabilities are not year specific, rather they are relevant for all the harvests associated with a particular crop, planting date, and high tunnel design. The probability distributions were fit based on all the harvests from each scenario.
[y]SL = single layer of plastic, DL = double layer, DL+B = double layer plus barrels, L = lettuce, S = spinach.
[x]\$1.00/lb = \$2.2046/kg.

Table 4. Percentage chance of positive returns at different crop selling prices and various scenarios, Las Cruces, NM, cooperator site, double-layer high tunnel design.

Scenario (crop, planting mo.)[z]	Chance of positive returns (%)					
	Sale price (\$/lb)[y]					
	2.00	3.00	4.00	5.00	6.00	7.00
L, October	87	97	99	100	100	99
L, November	57	76	86	91	93	95
L, December	77	92	97	98	99	99
S, October	57	86	97	99	100	100
S, November	19	48	70	83	90	94
S, December	30	45	55	62	67	71

[z]L = lettuce, S = spinach.
[y]\$1.00/lb = \$2.2046/kg.

returns for lettuce were quite low in the DL+B design, 56% in October and 9% in November at $2.00/lb (Table 3).

The higher yields and lower costs in the SL and DL models allow for higher probabilities of positive returns at lower crop selling prices, compared with the DL+B design, which indicate the lower-cost designs may be the best choices in Las Cruces for spinach and lettuce production.

Las cruces results: cooperator data. Simulation results for lettuce at the Las Cruces' cooperator site (DL model only) showed very favorable probabilities, even for late plantings (Table 4). Lettuce planted in December had a 77% probability of having positive returns at $2.00/lb and 97% at $4.00/lb. However, the best planting date for lettuce was October, with an 87% probability at the $2.00/lb price level and 100% probability at $5.00/lb. However, a late planting of lettuce in the DL design may allow farmers more latitude in scheduling the use of the structure, especially when prices are higher than $3.00/lb.

Spinach planted in December had lower probabilities than lettuce, and December was the riskiest planting date because a price point of $7.00/lb was needed to achieve a probability of positive returns of 70%. The best planting date for spinach was October, with a 57% probability of having positive returns at $2.00/lb and 99% at $5.00/lb.

Simulation results: Alcalde. In Alcalde (northern New Mexico, where seasonal temperatures are lower), the probability of returns exceeding zero was lower at the same price levels compared with those in Las Cruces (Table 5). Even at a price point of $7.00/lb, the percentage chance of making a positive return exceeded 80% in Alcalde in only 7 of the 12 scenarios, and 5 of those cases were lettuce.

Using a $4.00/lb price for lettuce produced in Alcalde, all three tunnel designs at both planting dates had probabilities of positive returns exceeding 70%, except for the DL November planting (65%) (Table 5). For spinach at this price point, the SL and DL designs at the October planting date also had >70% probabilities of a positive return, whereas the DL+B design did not (50%).

The planting date for lettuce in the SL design in Alcalde had little impact on the probability of a positive return. For example, at $4.00/lb, the probabilities were 77% for the October planting and 75% for the November planting. In the DL design, the October planting for lettuce had a higher percentage chance of positive returns than the November planting (81% and 65%, respectively). In the DL+B model, both lettuce planting dates had similar probabilities (>70%) of a positive return at prices $4.00/lb and higher (Table 5).

In the case of spinach at $4.00/lb, the October plantings in the DL and SL models had a >70% change of positive returns compared with ≈50% chance in the November planting for both models, but in the DL+B, the October planting had only a 50% chance of positive returns. The November-planted spinach showed low probabilities of a positive return for all tunnel designs (30%, 48%, and 50% for DL+B, DL, and SL, respectively) (Table 5).

Therefore, late-planted spinach (November) in Alcalde carries a relatively large risk. This risk is particularly pronounced for late-planted spinach in the DL+B design. Thus, the DL+B design may only be an option for lettuce in Alcalde, for either planting date.

Sensitivity analyses. Sensitivity analyses were conducted for lettuce in all three tunnel designs (Table 6) and for spinach in the SL and DL designs (Table 7). The DL+B design was not analyzed for the case of spinach because it did not appear to be a viable option, based on the simulation results. Lettuce growers using the SL model could produce yields as low as 20 lb/tunnel and realize prices as low as $4.00/lb and cover the costs of the materials and seed by $35.30, whereas the DL growers would earn only $19.85 for the same price and yield combination, after subtracting materials, seed, and electricity costs. In the DL+B case, the same price and yield combination would result in $8.31 returns. These results reflect the higher costs of building the DL and DL+B tunnel designs.

In the case of spinach, at the $4.00/lb selling price and yield of 26 lb for the entire tunnel during a 4-month harvest season, the returns after subtracting tunnel material costs, seed, and electricity to run the fan (the latter for the DL model only) were estimated to be $59.30 and $43.85 for the SL and DL models, respectively (Table 7). Whether those returns are adequate to cover land, labor, irrigation, and management costs must be determined by the individual grower. However, it is likely that without a significant increase in productivity these returns would be unacceptable to many producers. Other studies have documented a broad range of economic outcomes from high tunnels depending upon the structure, crop production, labor management, and other factors (Conner et al., 2010; Waldman et al., 2012). Under optimal management, individual growers may be able to maximize each of these factors to affect their chances of positive returns.

Table 5. Percentage chance of positive returns at different crop selling prices and in various high tunnel scenarios, Alcalde, NM.[z]

Scenario (tunnel design, crop, planting mo.)[y]	Chance of positive returns (%) Sale price ($/lb)[x] 2.00	3.00	4.00	5.00	6.00	7.00
SL, L, October	59	70	77	80	84	86
SL, L, November	60	69	75	79	81	84
SL, S, October	50	63	71	76	79	82
SL, S, November	29	42	50	56	61	65
DL, L, October	47	68	81	90	94	97
DL, L, November	40	56	65	71	75	78
DL, S, October	9	68	79	86	90	93
DL, S, November	23	37	48	55	61	65
DL+B, L, October	49	64	72	77	81	84
DL+B, L, November	57	69	75	79	82	84
DL+B, S, October	25	39	50	57	63	67
DL+B, S, November	11	22	30	37	43	48

[z]Probabilities are not year specific, rather they are relevant for all the harvests associated with a particular crop, planting date, and high tunnel design. The probability distributions were fit based on all the harvests from each scenario across all years.
[y]SL = single layer of plastic, DL = double layer, DL+B = double layer plus barrels, L = lettuce, S = spinach.
[x]$1.00/lb = $2.2046/kg.

Table 6. Sensitivity analysis and estimated returns for high tunnel lettuce production across a range of actual yields and selling prices and three high tunnel designs: single layer of plastic (SL), double layer (DL), and double layer plus barrels (DL+B).[z]

Yield (lb/tunnel)[y]	Sale price ($/lb)[y] 2.00	4.00	6.00	2.00	4.00	6.00	2.00	4.00	6.00
	SL returns ($/tunnel)[y]			DL returns ($/tunnel)			DL+B returns ($/tunnel)		
5	(34.70)[x]	(24.70)	(14.70)	(50.15)	(40.15)	(30.15)	(61.69)	(51.69)	(41.69)
20	(4.70)	35.30	75.30	(20.15)	19.85	59.85	(31.69)	8.31	48.31
35	25.30	95.30	165.30	9.85	79.85	149.85	(1.69)	68.31	138.31
50	55.30	155.30	255.30	39.85	139.85	239.85	28.31	128.31	228.31
65	85.30	215.30	345.30	69.85	199.85	329.85	58.31	188.31	318.31
80	115.30	275.30	435.30	99.85	259.85	419.85	88.31	248.31	408.31
95	145.30	335.30	525.30	129.85	319.85	509.85	118.31	308.31	498.31

[z]Estimated returns are net of materials, seed, and electricity costs (the latter for DL and DL+B only). These returns apply to both Alcalde, NM, and Las Cruces, NM, since costs particular to each site were not included, such as labor.
[y]$1/lb = $2.2046/kg, 1 lb/512-ft² (47.6 m²) tunnel = 85.0781 lb/acre = 95.3599 kg·ha⁻¹, $1.00/tunnel = $85.0781/acre = $210.2326/ha.
[x]Parentheses within the table indicate negative returns.

Table 7. Sensitivity analysis and estimated returns for high tunnel spinach production across a range of actual yields and selling prices, single-layer (SL) and double-layer (DL) high tunnel designs.[z]

Yield (lb/tunnel)[y]	Sale price ($/lb)[y] 2.00	4.00	6.00	2.00	4.00	6.00
	SL returns ($/tunnel)[y]			DL returns ($/tunnel)		
2	(40.70)[x]	(36.70)	(32.70)	(56.15)	(52.15)	(48.15)
10	(24.70)	(4.70)	15.30	(40.15)	(20.15)	(0.15)
18	(8.70)	27.30	63.30	(24.15)	11.85	47.85
26	7.30	59.30	111.30	(8.15)	43.85	95.85
34	23.30	91.30	159.30	7.85	75.85	143.85
42	39.30	123.30	207.30	23.85	107.85	191.85
50	55.30	155.30	255.30	39.85	139.85	239.85

[z]Estimated returns are net of materials, seed, and electricity costs (the latter for DL only). These returns apply to both Alcalde, NM, and Las Cruces, NM, since costs particular to each site were not included, such as labor.
[y]$1/lb = $2.2046/kg, 1 lb/512-ft² (47.6 m²) tunnel = 85.0781 lb/acre = 95.3599 kg·ha⁻¹, $1.00/tunnel = $85.0781/acre = $210.2326/ha.
[x]Parentheses within the table indicate negative returns.

Conclusions

Season extension technology is an important tool for small-scale growers. By extending the growing season without incurring prohibitive costs, farmers can better manage their risk and cash flow. In the southwestern United States, with its mild winters and abundant sunshine, high tunnel technology is a promising approach to season extension. This study examined the economic implications of using three high tunnel designs at two locations in New Mexico, at two different planting dates, and two leafy crops (lettuce and spinach) in the winter months. This analysis focused on winter production and did not consider the income potential associated with using the structures during spring, summer, or fall, which could be significant.

Given the simulation results, the SL and DL designs appear to be the more appropriate technology for both locations for spinach, whereas the DL+B design might be a reasonable option for lettuce in Alcalde. The SL and DL models provided adequate protection for growing crops, were cheaper to build, provided more interior growing space, and resulted in higher probabilities of producing positive returns, compared with the DL+B design. The DL design performed similarly to the SL design, but requires running electricity to the structure to power the inflation fan. This cost could vary, depending on the fee structure and proximity on individual farms. In addition, wiring a high tunnel with electricity may change the status of the structure for taxation purposes and should be considered carefully.

Thus, this analysis examined in which cases growers can achieve high probabilities of covering material and seed costs for each of the three tunnel designs, for lettuce and spinach, at two locations in New Mexico using a simulation analysis. The probability information can help distinguish which cases may be too risky to even consider. If a grower can reasonably estimate a likely selling price in known location and establish a comfortable risk threshold, these tools allow for managerial decisions to be made for each scenario. In all cases, expected returns were higher using the SL design, given the results of the sensitivity analyses. Combining the risk and the sensitivity analyses provides growers with a unique evaluation process to make high tunnel design, planting date, and crop choices.

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