

COLD-CLIMATE GREENHOUSE RESOURCE

A guidebook for
designing and building a
cold-climate greenhouse

Southeast Regional Sustainable
Development Partnership

UNIVERSITY OF MINNESOTA
EXTENSION

CSBR
Center for Sustainable Building Research

**Eagle
Bluff**
Environmental
Learning Center

Center for Urban and
Regional Affairs (CURA)
UNIVERSITY OF MINNESOTA

This is a publication of the University of Minnesota's **Center for Urban and Regional Affairs (CURA)** and **Center for Sustainable Building Research (CSBR)**, with additional funding and facilitation from the University of Minnesota **Southeast Regional Sustainable Development Partnership (RSDP)**.

CURA connects the resources of the University of Minnesota with the interests and needs of urban communities and the region for the benefit of all. The content of this report is the responsibility of the authors and is not necessarily endorsed by the Community Assistanceship Program, CURA or the University of Minnesota.

CSBR's mission is working to transform the built environment in ways that provide for the ecological, economic, and social needs of the present without compromising those of the future. Design for Community Resilience, a program of CSBR that was involved in this project, works with MN communities to transform civic challenges into sustainable opportunities through design.

The mission of the Southeast RSDP is to work with citizens in southeastern Minnesota to create and sustain healthy ecosystems, strong local economies and vibrant, self-reliant communities. The Regional Partnerships bring together local talent and resources with the University of Minnesota knowledge to drive sustainability in agriculture and food systems, tourism and resilient communities, natural resources and clean energy. The Partnerships are part of University of Minnesota Extension.



© 2013 by The Regents of the University of Minnesota.

This work is licensed under the Creative Commons Attribution---NonCommercial-ShareAlike 3.0 Unported License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-sa/3.0/> or send a letter to Creative Commons, 444 Castro Street, Suite 900, Mountain View, California, 94041, USA. Any reproduction, distribution, or derivative use of this work under this license must be accompanied by the following attribution: "© The Regents of the University of Minnesota. Reproduced with permission." Any derivative use must also be licensed under the same terms. For permissions beyond the scope of this license, contact the CURA editor.

This publication may be available in alternate formats upon request.

Center for Urban and Regional Affairs (CURA)
University of Minnesota 330 HHH Center
301—19th Avenue South
Minneapolis, Minnesota 55455
Phone: (612) 625-1551
E-mail: cura@umn.edu
Web site: <http://www.cura.umn.edu>

The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race, color, creed, religion, national origin, sex, age, marital status, disability, public assistance status, veteran status, or sexual orientation.

To download a copy of this report as a .pdf, please visit
<http://csbr.umn.edu/publications/reports.html>



**Southeast Regional Sustainable
Development Partnership**

UNIVERSITY OF MINNESOTA
EXTENSION

Center for Urban and
Regional Affairs (CURA)

UNIVERSITY OF MINNESOTA

Printing assistance generously provided by:





Paradox Farm cold climate greenhouse Photo: Sue Wika

Contents

| | |
|---|----|
| Section I: Introduction | |
| Acknowledgments | 4 |
| Executive Summary | 6 |
| Cold Climates + Food Security | 7 |
| Research Methodology | 8 |
| Section II: Design Considerations | |
| Defining Priorities | 11 |
| Production System: What to Grow | 15 |
| Orientation Towards the Sun | 17 |
| Site and Space Planning | 19 |
| Documentation and Monitoring | 21 |
| Section III: Greenhouse Components | |
| Greenhouse Components | 23 |
| Foundations | 24 |
| Soil and Containers | 25 |
| Greenhouse Frames | 27 |
| Light/Glazing | 29 |
| Heat — Keeping the Greenhouse Warm | 34 |
| Ventilation | 38 |
| Operable Insulation | 39 |
| Irrigation | 40 |
| Interior Layout | 41 |
| Appendix | |
| Links and Resources | 48 |
| Survey Results | 49 |
| Bibliography | 63 |

Section I: Introduction

Acknowledgments

This project is a joint effort of Eagle Bluff Environmental Learning Center near Lanesboro, MN, the University of Minnesota Extension Southeast Regional Sustainable Development Partnership (SERSDP), the University of Minnesota Center for Urban and Regional Affairs (CURA) Community Assistantship Program, and has been conducted by the Design for Community Resilience Program at the University of Minnesota's Center for Sustainable Building Research (CSBR).

Project Team

Joe Deden, Director, Eagle Bluff Environmental Learning Center
 Erin Meier, Program Director, SE Regional Sustainable Development Partnership
 Virajita Singh, Senior Research Fellow, Center for Sustainable Building Research
 Dan Handeen, Research Fellow, Center for Sustainable Building Research
 Jody Rader, Research Assistant, Center for Urban and Regional Affairs
 Greg Schweser, Community Food Systems Planner, Regional Sustainable Development Partnership

Greenhouse Growers, Designers, & Builders

We thank the following people and groups who graciously took time out of their busy schedules to host visits and answer many questions for this research:

Jeffrey Boggs, Lanesboro High School Superintendent
 Arlene Jones, The Farm on St. Mathias
 Jason Eden, RREAL
 John and Lissa Sumption, King Gardens
 Chuck Waibel and Carol Ford, Garden Goddess
 Liz Belina, Liz's Greens
 Women's Environmental Institute
 Easy Bean Farm
 Lonny and Sandy Dietz, Whitewater Gardens
 Tim and Shelly Elkington, Elk's Bluff
 Lorri Maus and Nathan Maus
 Eric Kreidermacher, Pork and Plants
 Phil Rutter, Badgersett Research Farm
 Harriet Behar, Sweet Earth Farm
 Tim Kenny, The Learning Center at the Minnesota Landscape Arboretum
 Sue Wika, Paradox Farm

Report Production Team

Jody Rader, Research Assistant, CURA
 Dan Handeen, Research Fellow, CSBR
 Virajita Singh, Senior Research Fellow, CSBR

We would also like to thank all those who participated in the online survey of greenhouse growers and sustainable agriculture organizations for their time and input.

Dedication

While traveling around Minnesota and Wisconsin for our research, we met many people who have committed their hearts and energy to growing vegetables during the winter; something that most people believe is impossible. Chuck Waibel and Carol Ford have not only done this, but they have also dedicated their time to sharing what they have learned with others, while creating networks where people can come together and share. Nearly every grower interviewed for this project attributed a part or much of their design, motivation, and knowledge of their greenhouse to Chuck and Carol. The Garden Goddess greenhouse is iconic across the region, and Chuck and Carol's name is synonymous with fostering this growing network of greenhouse growers.

This report is dedicated to Chuck Waibel, who passed on as this report was being completed. His contributions and inspiration will never be forgotten.



Chuck Waibel, 1958-2013

Executive Summary

The local foods movement in the Midwest is thriving, today. Consumers have become increasingly aware and concerned that the food that they are purchasing and eating is healthy, free of hormones and pesticides, and has not traveled long distances to reach the table. According to the 2008 Farm Act, a product can be marketed as locally or regionally produced if its end-point purchase is within 400 miles of its origin, or within state boundaries. A 2009 study by the Food Marketing Institute asked Americans why they buy local. Eighty-two percent responded that freshness was the driving factor, 75% responded that they preferred to support the local economy, and 58% responded that they prefer to know where their food is coming from.

The Midwest is known for fertile soil, which provides the country (and the world) with commodities such as corn, soybeans, and wheat. Vegetable, fruit, and nut production is practiced, but not to the degree of cash crops. Because the growing season is short, it is assumed that food production is not possible year-round. This significantly limits the possibilities of locally-produced food in cold regions. However, there are a handful of pioneering growers across the Midwest who have chosen to grow year-round, or to grow exclusively during the winter. They have been able to do this using cold-climate greenhouses.

Greenhouse growing is not a new technology, and greenhouses that are not completely dependent on conventional heating methods (fossil-fuel based heaters) have been experimented with since the late 1960s. Today, burning of fossil fuels is well understood to be both fiscally and environmentally costly. Decreasing dependence on foreign fuel sources is a legitimate concern, and tightly linked with food security.

The purpose of this research and this guidebook is to document and highlight the successes and lessons learned by small growers across

the Midwest who have designed and built cold-climate greenhouses, and are actively growing produce during the winter. The focus here is on the architecture, assembly, materials, and building techniques that have yielded efficient greenhouses. The goal is to provide simple, time-tested techniques, as demonstrated by modern growers within the region.

The Cold Climate Greenhouse Resource is divided into three sections:

Section I: Introduction This is a narrative of the research methodology along with motivations for cold climate greenhouse production.

Section II: Design Considerations Here, site factors such as orientation, priorities, documentation, and general space planning are discussed.

Section III: Greenhouse Components This section breaks down the building components of cold climate greenhouses and compares materials and technologies.

Providing a survey of the most common successful components and designs is intended to help new winter producers make decisions, and to raise the awareness of these practices. A common thread discovered in this research relates to the number of years invested in experimenting with greenhouse designs: As with any farm operation, greenhouse growing is a work-in-progress. Every year brings new experiences, informing the next to increase efficiency, productivity, and value to the operation. By understanding the options that exist and what has worked for similar sites and farmers from the outset, the time it takes for new growers to reach a level of success should be decreased, strengthening the local food movements throughout the year in cold climates.

Cold Climates + Food Security

Empowering small, sustainable farms to do what many think is impossible

Surviving in today's economy as a farmer subject to the typical Midwestern growing season is difficult. For many, the thought of attempting to grow food during the winter months in climates that reach sub-zero temperatures for weeks-on-end seems like a fantasy. As we have seen and documented through this research, this idea is not impossible. By learning from other growers' examples and providing affordable options, we hope to inspire more farmers to venture into winter production using passive-solar methods.

Health Benefits: Providing year-round options for fresh food in small communities

Today, many communities and neighborhoods are located in what we now know as 'food deserts'. These are areas that do not have access to fresh fruit and vegetables. Increasing the possibility of local production through increased access to year-round facilities can create healthier options for both rural and urban communities.

Increasing the knowledge base of sustainable agricultural practices

Many farmers across the United States and around the world have been producing winter vegetables using greenhouse methods for years. Many of these farmers are operating quietly, without a community of other farmers with whom to share knowledge and expertise. Nearly every person who was contacted or interviewed for this research expressed a desire to share and learn from other growers' experiences in building and growing in a winter greenhouse.

Decreasing miles traveled for fresh food, decreasing carbon-footprint and emissions

The conventionally-grown produce that makes its way to grocery stores across the upper Midwest often travels thousands of miles, and often by diesel truck. This increases greenhouse gas emissions and places a burden on the already fragile and expensive national transportation network, not to mention the depletion of the fossil fuels on which this system depends. Such long trips can also mean that food is often sold after it has passed its peak freshness and nutritional value.

Research Methodology

The majority of the research and documentation for this project was conducted during the summer of 2013. With the intention of combining first-hand experience of growers with practical technical building science, the research methods required a multi-faceted approach. In the early stages of research, most information was gathered through literature written during the mid-1970s to mid-1980s. These texts were surely a result of the times; an interest in sustainable, small-scale growing and independence from oil had grown out of the energy crisis of the 70's. Innovation and creativity in small-scale design resulted in a handful of greenhouses that are shaped like geodesic domes, would partially heat adjacent homes, are built underground, use all salvaged materials, and so on. This interest seems to have waned during the 90's and early 2000's, as fewer passive greenhouses are documented during this time. However, two growers, Anna Edey and Eliot Coleman, greatly influenced innovation and continuation of winter greenhouse growing throughout the 80's, 90's, and 2000's. Today, most publications detailing winter greenhouse technologies are produced in the form of technical bulletins from university extension offices around the country. *Season extension* is a commonly-used term to define this practice at a larger scale.

The knowledge gathered and shared through texts, written by growers, builders, and designers, is quite useful for gaining familiarity with winter greenhouse design. However, this could only bring the research so far; the task was to find what growers are actually doing.

To the right are some of the initial questions that framed the scope of research:



Schematic design of a passive-solar greenhouse from Anna Edey's influential book, Solviva (1998). Image: solviva.com

What are people able to grow in Climate Zone 4 during the coldest months of the year?

How are they keeping their greenhouse warm?

What is warm enough?

How are materials sourced?

What do passive-solar greenhouses look like?

Are growers able to stay afloat, or even make a profit, while competition from imported fruits and vegetables from warm climates flood grocery stores?

Is winter growing even a viable possibility for food security in colder climates, or is this simply an expensive and difficult hobby for growers on the fringes?

It was obvious that interviews and regional farm visits would yield answers to these questions. Over the summer of 2013, fifteen greenhouses were visited and over fifteen growers from across Minnesota and Wisconsin were interviewed. Many of the contacts made were through word-of-mouth referrals from one grower to the next.

After the first few visits it became clear that gaining a wider view of both local and other cold-climate regional practices would be beneficial for the research. Each structure was slightly different, and every grower had invaluable experience and lessons to share. It also became very apparent that there wasn't one particular design solution for optimizing greenhouse design: Site specifics, plant varieties, schedules, labor, and start-up budgets all play a key role in decision-making before and throughout the winter growing process. In an attempt to gather as many experiences as possible, an online survey was sent out to over 100 growers and sustainable agricultural organizations throughout the upper Midwest, and extending throughout North America. These survey results (see appendix) gave an detailed view of what and how various growers are operating during the winter.



Farm visit to Lorri Maus' greenhouse Photo: Virajita Singh

Section II: Design Considerations



Defining Priorities

It is important to understand and define exactly *why* one is looking to start a cold-climate greenhouse. These priorities will influence the structure, design, and size of the greenhouse, as well as the planting schedule, number of people required to maintain the greenhouse, and the way in which the greenhouse fits into existing infrastructure. The following pages identify common uses and priorities for smaller-scale greenhouse operations, along with commentary on the ramifications of each.

For each grower, the measure of success is particular to the goals and priorities set forth. High profit, low carbon footprint, educational milestones with children and community members, or simply the ability to do what many think is impossible (growing vegetables in the dead of winter!), are all measures of success. As a grower, knowing one's priorities and intentions along with understanding that the first few years of the greenhouse operation should be treated as probationary and experimental will help the success of the greenhouse -- no matter how the grower defines it.



View from bluff at Whitewater Gardens Photo: Jody Rader

Priorities: 1. Winter-optimized Production

There is a small yet growing enthusiasm for winter-optimized greenhouses. These greenhouses are particularly innovative, as they have been designed specifically to operate during the coldest times of the year, when the sunlight is at a minimum. The majority of these growers are using or experimenting with passive solar and alternative energy heating methods in order to keep utility bills low or non-existent. Keeping utility bills low for winter greenhouses is the key to their viability; the operating cost to maintain optimal temperatures for growing even the hardiest of vegetables in climates similar to those found in Minnesota during the dead of winter would surpass profits. In these greenhouses, there are typically two different reasons for heating: one for the plants, which tends to manifest as heat storage and recovery methods, focused on heating the soil; and a heating system such as a wood stove or forced air heater that is used for the comfort of people working inside of the greenhouse during the cold winter months.

The design is driven by creating a space that is able to capture as much light and heat from the sun as possible, and re-distribute this heat during the nighttime. Therefore, the north side of the building is generally *not* glazed and made of an opaque, insulated wall. Results with earth-bermed designs for the north wall have been particularly successful. The glazing is oriented due south, with glazing angles intended to be as close to perpendicular to the angle of incidence of sunlight around December 21st, the shortest day of the year.

During the summertime, after the final spring harvest, these greenhouses are typically empty, or used for storage until the fall, because temperatures are too high for working during the summer months. If growing directly in the ground, this is a great time to ‘bake’ the enclosed soil as a way to decrease pests and disease inside the

greenhouse. One grower uses their greenhouse as a dehydrator during the summer. Because there isn’t any active planting or harvest during the summer months, these greenhouses are considered winter-only buildings.

Growers who embark on the winter-optimized production schedules tend to have smaller greenhouses, with only one or two people needed to tend them for a few hours per week (outside of seeding and final harvesting times). A winter CSA operation may be appropriate for this schedule of production, as it provides fresh produce during the winter months that will be valued at a premium over imported varieties found at grocery stores. If there is an opportunity for a winter farmers’ market in the grower’s community, winter greenhouse growers can distinguish their products from the other items sold, which tend to be non-perishable items or goods created from root vegetables or frozen vegetables harvested in the fall. Generally, the winter-only greenhouses produce hardy and tender greens, with an emphasis on salad mixes. Commonly, winter greenhouses are used to start seedlings in the late winter/early spring which are then transplanted outdoors in the later spring.



Elk's Bluff winter-only production greenhouse Photo: Jody Rader

Priorities: 2. Year-round Production

There is quite a bit of overlap between the design, structure, and use of a year-round greenhouse compared to a winter greenhouse. The differences are subtle, and oftentimes, in the process of determining the best annual schedule for output, a grower may shift their greenhouse back and forth between year-round and winter-only use.

Placing a priority on year-round production essentially means that the grower has three or four seasons of activity occurring in the greenhouse. Because the greenhouse has to accommodate below-zero temperatures during the winter and excessive heat during the summer, the structure needs to be versatile and have extremely efficient insulation and ventilation systems in place. The successful greenhouses operating in a year-round schedule generally do not rely solely on passive solar methods for heating during the winter, and instead rely on alternatively-fueled heat sources such as pelletized hydronic systems or geothermal heat pumps. These heating systems have a higher up-front installation costs but provide guaranteed and consistent heating throughout the season.

Generally, contemporary year-round production operations are larger greenhouses serving a retail or wholesale market. The larger facilities require either a more sophisticated automated system for temperature control, or require more hours dedicated to watering, monitoring, and tending to the crop. However, year-round production does not exclude smaller operations.

The larger, year-round greenhouses tend to be built from modular, pre-manufactured kits (as opposed to site-built lean-to designs common in winter-optimized greenhouses), which allows easier addition to the greenhouse operation over time. Gutter-connected designs with full ridge-vents and polycarbonate glazing or polyethylene sheeting are common with successful greenhouses in this category.



Tomatoes are grown year-round in the greenhouse at Whitewater Gardens Photo: Dan Handeen

Priorities: 3. Education

Greenhouses constructed, built, and maintained for the purpose of education are a growing trend in schools and educational centers across the upper Midwest and throughout the nation. Here, greenhouses serve as an indoor/outdoor classroom where kids and adults are encouraged to learn about a variety of subjects such as plant propagation and botany, food systems, and production methods. The range of success for these greenhouses is wide. Unfortunately, many school greenhouses are built through large grants and spearheaded by an enthusiastic faculty member or student group. The enthusiasm for the project is subject to wane as staff members change positions or kids graduate, taking with them the motivation to keep the greenhouse functioning. Many of these educational greenhouses have now become very expensive (and warm!) storage buildings on their campuses.

This is not to say that all educational greenhouses are subject to failure. Successful precedents do not overlook the importance of planning. It is imperative that a greenhouse that prioritizes education has clear leadership and oversight, and that the detailed goals and principles illustrated in the greenhouse are determined prior to construction.

Some key considerations for educational greenhouses relate to overall layout and comfort for the users (students and teachers). An area large enough for small gathering, possibly around tables, is necessary for teaching planting methods. Maintaining good sight lines throughout the greenhouse is key, if a teacher is expected to educate large numbers of younger children. Similar to the winter greenhouse, multiple heating methods may be necessary in order to accommodate both the plants and the people who will be using the greenhouse. Successful educational greenhouses tend to be run in conjunction with good indoor facilities (classroom areas, teaching kitchens), and with gardens.

Determining the specific program to be offered may also influence the structure or design. Public schools tend to operate on semester schedules, with a few weeks of vacation over the holidays in December and early January. This means that during the coldest times of the year, the greenhouse may potentially be vacant. This means that a season-extension style may be more suitable (a high-tunnel design versus a year-round or winter-only greenhouse design), and less expensive to purchase and install.

It is tempting for educators to try to make the greenhouse function at high levels for too many goals. For instance, many greenhouses are intended to both serve as educational tools demonstrating the life-cycles of plants and how food systems work, in addition to high-output production (supplying the school cafeteria with all of the vegetables for the school year, for instance). This is a tricky act to balance and maintain, as kids are not day-laborers, and lesson plans may not coincide neatly with growing, harvesting, watering, and maintenance schedules needed to maintain a high-production facility. Tim Kenny, the director of the Learning Center at the Minnesota Landscape Arboretum has extensive experience designing and implementing educational experiences for kids to learn about plants over the last thirty years. He cautions any educator from trying to over-program a greenhouse, and recommends keeping the goals simple and attainable.

Production System: What to Grow

Determining what to grow is heavily dependent on the targeted market, end-users of the produce, and the priorities identified by the grower. Some models and suggestions follow:

Small Winter CSA/Farmers' Market/Family or Neighborhood Winter Food Supply

If a grower is looking to provide produce to supply for a winter CSA market, a variety of vegetables and herbs will be more economically sustainable in the long run. CSA stands for *Community Supported Agriculture*, and is an economic model of agricultural distribution. Families or individuals purchase a “share” of the farmer’s yield, which is delivered regularly. The consumer benefits from having fresh, local, and seasonal produce, and the farmer is assured a financial commitment from the buyer.

Weekly, or bi-weekly shares need to accommodate families’ dietary needs and desires. A share that contains hardy and tender greens (kale, mustard greens, salad greens, and various herbs), along with an offering of onions, carrots, and root vegetables will result in satisfied customers who can viably utilize the CSA share to supply their produce needs throughout the winter. If a family purchases a CSA share, but then is unable to use the type of vegetables appropriately during the winter, they will turn to supplementing their grocery needs with imported vegetables found at the supermarket at added cost. This can decrease repeat customers year-to-year, as it will not be economically feasible for a family.

A winter CSA may also require creative marketing and raising awareness amongst customers of the value of eating seasonally and locally. Some growers collaborate with other local winter farms in order to combine produce, in order to provide variety. Elk’s Bluff winter CSA teams up with another grower to trade vegetables in order to do just this. Having a root cellar (underground structure designed to store vegetables at a steady, cool temperature) to store potatoes and other root vegetables over the winter can add value to the shares with minimal effort throughout the winter season. An earth-bermed greenhouse structure works well in combination with a root cellar. The small winter CSA/farmer’s market and family/neighborhood winter food supply growing selection lends itself well to the winter-only greenhouse model, due to the size of the greenhouse and the time involved to manage the operation.



Winter CSA share from Eco City Farms in Prince Georges County, MD
Photo: www.ecoffshoots.org/front-page/food/winter-csa-eco-city-farms/

Restaurant/Wholesale/Retail

If the intended market for the greenhouse operation is restaurants, wholesale or retail markets, the grower tends to lean toward specialty crops or premium produce items that may be difficult for consumers and restaurants to obtain fresh or locally during the winter months. Solviva, Garden Goddess, and many winter greenhouse operations have touted the success of developing specialty mixed greens that can save restaurants time and money in washing and processing, and the grower can then charge a higher price for such goods and services. Growers may also choose to grow tomatoes during the winter for similar reasons, as they may be able to get a better price for higher-demand 'off-season' vegetables that have been locally-produced.

The type of greenhouse that lends itself well to this type of production is the medium-to-larger operation, or the year-round operation, which can produce a steady supply throughout the year. Aquaponic and hydroponic operations also lend themselves well to this model, because seasonal variability is lower. Some growers who produce for retail markets also tend to grow perennial and annual garden and house plants for sale, in order to sustain income throughout the year. Sweet Earth Farm and Pork and Plants are both successful examples of combining plant sales with vegetable or livestock sales.



Greens used for mixes from Labore Farms

Photo: msmarket.coop/files/labore-kateNGsommers-for-heavytable.jpg

Education

Scrutiny and attention to the audience is extremely important when determining what to grow in an educational greenhouse. While growing leafy greens during the winter may be exciting and interesting for educators and those already interested and aware of local food systems, kids may not find the value of such crops and therefore may lose interest in the subject matter. Growing vegetables and plants that have an immediate 'taste' experience for kids can create a lasting impression. Again, here it is important to distinguish the reality of growing vegetables for educational tools while meeting the production needs of a school cafeteria. Children and their parents will benefit from growing interesting and tasty varieties in the greenhouse, and will make the farm-to-plate connection if they are growing items that they are already familiar with, or already eat.



Tables arranged to activate the senses at the Learning Center at the Minnesota Landscape Arboretum Photo: Jody Rader

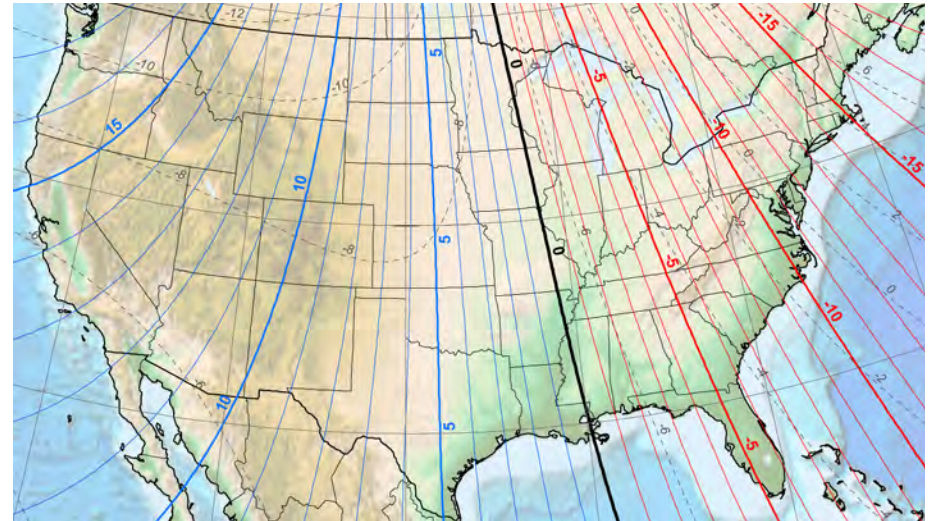
Orientation Towards the Sun

Quite possibly the largest design consideration when planning a winter or year-round greenhouse is determining the orientation and angle of glazing for the structure. After interviewing and surveying Midwestern growers for this research, it seems apparent that orientation of the greenhouse is something that is often overlooked or underestimated at the beginning of the design and construction phase. While many other components can be tweaked or changed after a few years, the overall angle of the glazing and the direction of the structure is difficult to change.

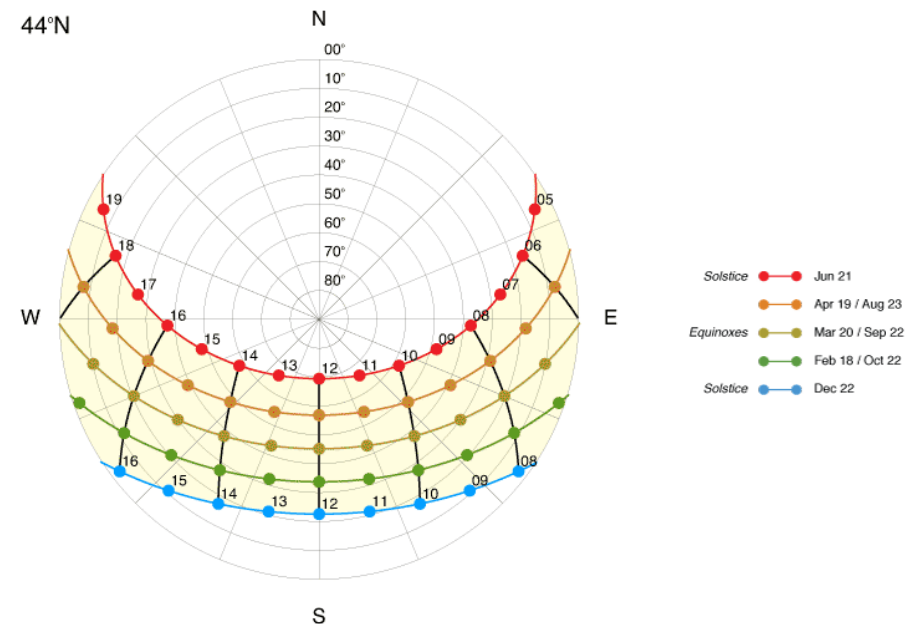
In general, growers optimizing for winter growing should orient their greenhouse in an east-west direction, meaning that the longer, glazed side of the greenhouse should face south, with the shorter ends facing east and west. In order to maximize the amount of sunlight entering the greenhouse during the shortest time of year, that it is important to look at a sun path chart for your latitude, along with a current magnetic declination map to determine 'solar south' for your latitude. A compass will direct one towards magnetic north and south, which is a reading of where the magnetic poles are located on earth, not where the axis of the tilt of the earth exists. Depending on where one is located geographically in the United States, true north may be up to 23 degrees to the east or west of magnetic north. **For southeast Minnesota, true south is approximately 1-2 degrees west of magnetic south.**

Here is a website that gives many methods for finding true north/south: http://rimstar.org/renewnrg/finding_true_south_pole.htm.

Here is a website that is helpful for plotting sun paths: <http://solardat.uoregon.edu/SunChartProgram.html>



Magnetic Declination Map, 2012 Image: NOAA

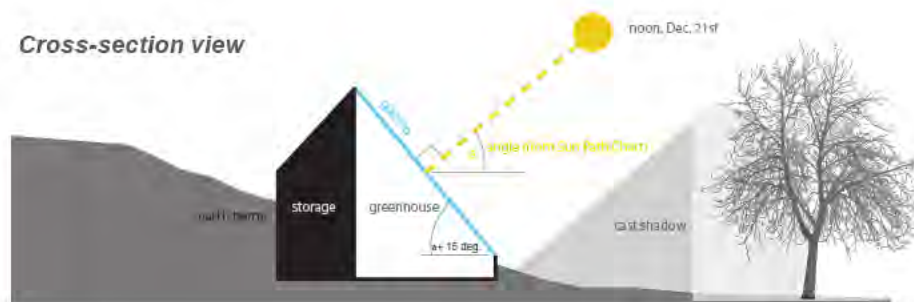
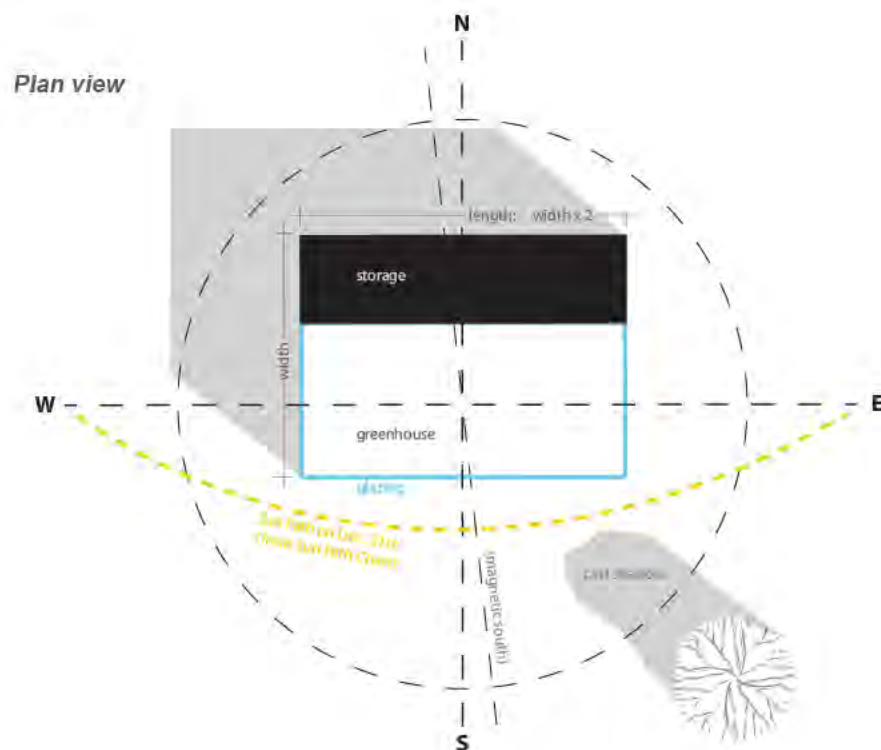


Sun Path Chart for 44°N Latitude Image: University of British Columbia

In order to minimize shadows created by the structure itself, it is generally recommended to have a length-to-width ratio of 2:1 as a minimum. Because the northern side of the greenhouse in Minnesota will never receive and capture direct sunlight, placing glazing on the North side will only contribute to heat loss, especially during evenings and nights when the temperature drops. Therefore, the greenhouse should be either attached to the south side of an existing structure, or build the north wall of the greenhouse as an opaque wall with both thermal storage and insulating qualities, preferably 'bermed' or built into sloped earth. Earth berming also creates a windbreak for the structure during the winter months, when the predominant wind direction is from the North.

Growers who are intending to produce year-round or simply extend their typical growing season may choose to orient the longer dimension of their greenhouse in a north-south direction. This orientation, in conjunction with a properly sized ventilation system, will help to prevent overheating during the summer months while taking advantage of the prevailing winds for ventilation. However, optimal *winter* solar gain is sacrificed with North-South orientation.

The angle of incidence is the angle with which sunlight hits the surface of the glazing in the greenhouse. For optimal solar heat gain, it is important that the glazing is nearly perpendicular to the angle of incidence during the coldest and shortest days of the year. Finding the angle of the sun for December 21st for the greenhouse latitude will determine this angle. (See Sun Path Chart on previous page). **As a rule of thumb, one can find the optimized angle of incidence by adding 10-15 degrees to the degree of latitude for the greenhouse.**



Site Considerations Images: Jody Rader

Site and Space Planning

Site planning for the greenhouse is highly specific to each project. **It is important to take inventory of your property during different times of the day to determine where the greenhouse can be placed so as to avoid shading from nearby trees or structures, and to ensure that the desired solar gain can be achieved** (see previous section, *Orientation Towards the Sun*). In an urban setting, placement of a winter greenhouse on a property may not be reasonable due to shadows cast by nearby trees and neighboring structures. A solar design tool called a Solar Pathfinder can help to determine the best location and provide a very accurate estimate of the amount of sunlight the greenhouse will receive throughout the year. Contact the nearest extension office for information on where to find a Solar Pathfinder. Cell phone apps and experienced solar consultants can also accurately assess site solar potential.

Along with avoiding obstructions, the site should be assessed for potential hazards, such as dead tree limbs which could fall and damage the structure. Similarly, placement near a gravel road where large rocks may be kicked up from vehicle traffic may be hazardous, especially if glass is used for the glazing material. Finally, the greenhouse should be located out of the direct path of surface runoff water. If this is not possible, a swale or another conveyance method may need to be employed to avoid structural damage due to surface runoff.

Determining the route that will be used to enter the greenhouse is equally important. Often, greenhouses are constructed during the summer months, and the path from the barn, garage, house, etc. is not considered. **During the dead of winter, the grower will want to use the most practical path, perhaps doubling up with an existing driveway or walkway in order to avoid additional plowing or shoveling to enter the greenhouse.**

For winter and year-round greenhouses, it is important to avoid heat loss when doors are opened for accessing the greenhouse. Therefore, it is advisable to design the greenhouse with a vestibule or entryway with doors on both ends so that cold gusts of air do not enter directly into the greenhouse, and heat is not lost as readily to the outside. Many growers have attached (and heated) garages or processing rooms that serve as both a vestibule for entering the greenhouse and a warm area for washing and packing produce. There are a few growers that are utilizing efficient heat recovery methods to capture hot air that rises within the greenhouse and pumping it through an exchanger in a packing room in order to heat the packing room during the day.

The *Garden Goddess* greenhouse uses the simple innovation of attaching the greenhouse to a garage, which allows the winter produce to be washed, boxed, and packed into a vehicle for delivery without ever leaving the shelter of the greenhouse during the winter. This will save considerable time and headache during the winter months if a grower can design and construct their greenhouse adjacent to other spaces necessary for processing. Another tip provided by *Garden Goddess* is to store all anticipated soil and supplies in this packing space during the fall. The grower will then avoid having to haul bags of soil and other cumbersome supplies through the snow. The idea here is to make the greenhouse as contained as possible during the winter months, decreasing the time and energy needed to service the greenhouse when it is least desirable to be outdoors.

Harriet Behar's greenhouse near Gays Mills, Wisconsin and inspired by Anna Edey's *Sol/viva* design, utilizes cold frames along the southern side of the greenhouse. These cold frames are used during the late fall and into the winter for growing starts and vegetables. This allows quick access to the produce without having to enter the greenhouse, thus saving time and energy when packing. She can simply drive up to the southern exterior facade and load items directly into the back of a pick-up truck.



Garden Goddess Greenhouse attached to existing garage Photo: Jody Rader



Sweet Earth Cold Frames and area for pick-up Photo: Jody Rader

Documentation and Monitoring

Many of the growers interviewed for this research stressed the value in keeping detailed records and monitoring the greenhouse. This is even more important during the first few years of the greenhouse operation. There is not a one-size-fits-all approach to successful winter or year-round greenhouses due to the extreme variation in sites, crops, schedules, amount of sunlight, climate differences, and priorities of growers. It is important for each grower to keep a record of what works and what does not, in order to learn from year to year, and to increase output and efficiency. **A new greenhouse grower can expect to spend the first 2-6 years experimenting with schedules and strategies before reaching a comfortable level of operation.** Through accurate monitoring, record-keeping, and synthesis of results, this period of time should be reduced.

Carol Ford of *Garden Goddess* strongly suggests keeping a journal or a log in the greenhouse, and to post entries on a regular basis. This can be encouraged by setting up a system for entering information *before* the growing season is underway. Many growers monitor greenhouse air and soil temperatures, weather, and the growth of particular plants, days of harvest, etc.

Nearly every grower that we interviewed expressed some level of regret that they had not taken measurements or kept a detailed enough log from the beginning of their project. The type of data collected is unique to the grower and their priorities for success. The amount of time spent gathering data, and the degree of sophistication of logging is also particular to each grower's priorities. **Having a clear goal or priority for the greenhouse from the beginning, and dedicating effort to monitoring will undoubtedly save time and money in the long-run.**

Sharing information and lessons learned with other local growers is possibly the best way to gain information about particulars of cold climate greenhouse production. Innovators such as Chuck Waibel, have started online forums and regional groups to gather people together in a concentrated effort to share knowledge and build a community of support.

See <http://gardengoddessnetwork.ning.com/> for more information regarding the Deep Winter Producers' Association.



Open house at Garden Goddess, 2008 Photo: Chuck Waibel

Section III: Greenhouse Components



Greenhouse Components

This section outlines the various components found in all cold-climate greenhouses, whether intended for winter-use or year-round use. This assessment of materials, structural, and mechanical systems is intended as a survey of what is currently in use and what has been successful for growers across the upper Midwest, based on evidence gathered from this research. Information is derived from interviews with growers, survey results, and site visits.

There does not seem to be a one-size-fits-all combination of components that will create perfect conditions for growing. Each greenhouse project has individual parameters which dictate choices for each portion of the decision-making process. Growers are constantly tweaking their process and greenhouses each year, in order to optimize for the best results. Choosing materials and components which allow for flexibility down the road (for instance, having the ability to change the glazing material, or replace it, without compromising the entire structure), may be the best path for a greenhouse grower to take, whether novice or experienced.

The following discussion on greenhouse components is not exhaustive in content regarding all cold-climate greenhouse components. What is described here demonstrates a ‘snapshot’ of what is proving to be successful for growers throughout Minnesota and Wisconsin at the time of this research.



*Passive solar greenhouse at Laq Qui Parle High School (under construction)
Photo: Jody Rader*

Foundations

Foundations in cold climates need to be built into the earth below the frost line to avoid structural damage which can occur with the freezing of surface-level soil. In the upper Midwest, this generally means constructing a foundation that is at least four feet below grade. Below four feet, the soil temperature stays a steady 40-50 degrees year-round, despite large temperature swings above the surface. The depth of the foundation wall not only prevents the soil from freezing that would damage the structure, but also insulates the below-grade soil contained *within* the foundation stemwall. For winter and year-round greenhouse growing, especially if planting in the ground, maintaining optimal soil temperature is very important. By containing the soil within a continuously insulated foundation that is deeper than the frost line, the grower can reap the benefits of warmer soil during the winter.

The most common type of foundation used for greenhouse construction is a masonry or cast-in-place stemwall with a poured reinforced concrete strip footing. This wall should be insulated with at least 2 inches of polystyrene foam (preferably extruded polystyrene) insulation, installed continuously from the footing to the sill plate of the above ground structure. Some growers have also experimented by extending the insulation outward horizontally from the foundation wall, in order to further stabilize soil temperature. This method is known as a Frost-Protected Shallow Footing.

Regardless of the grower's priorities, the type of vegetables being grown, whether the plants are grown in the ground or in containers, or the type of structure that will exist above ground, a sufficiently deep foundation is necessary in order to keep the greenhouse warm during the winter months.

It is worth noting that in one case, a grower constructed a winter greenhouse for container growing on an a large existing concrete slab. While this was an efficient reuse of resources and provided a very workable surface, the concrete slab acted as a large heat fin that conducted heat out of the greenhouse to the ambient winter air. This unfortunate effect could be avoided by placing insulation between the underside of the greenhouse floor and the pre-existing slab to continuously isolate the thermal enclosure of the growing environment.



***Insulated Concrete Form foundation at Lac Qui Parle Valley H.S. greenhouse.
Note EPS insulation on both interior and exterior sides of concrete stemwall.
Photo: Jody Rader***

Soil and Containers

The decision to grow directly in the soil of the greenhouse versus in trays or in raised beds is dependent on a number of factors which should be weighed before construction, as this decision dictates both the horizontal and vertical configuration of the interior layout. Planting directly into the ground may result in some discomfort, with the grower having to bend over to work in the greenhouse. Planting in raised beds, trays on tables, or vertical hanging trays generally contribute to the comfort of the grower.

A year-round greenhouse will likely have a combination of planting containers, trays for starter plants, to be transplanted later either into soil within the greenhouse, or to an outdoor garden.

A winter-only greenhouse is well-suited for planting directly into the ground, if the foundation is deep and well-insulated. The root systems will stay warmest this way, especially with the integration of a heat recovery system installed below the growing area. During the summer months, when the winter-only greenhouse is not producing, temperatures may reach above 130°F, especially if ventilation systems are not in use. This can be beneficial for future crop health, as the intense heat will kill off diseases and pests, and render the soil sterilized for use in the fall when planting resumes. At 150° for only 30 minutes, soil-borne pathogenic bacteria and fungi, damping-off and soft rots, and nematodes are killed (McCullough 1978, 256).

The quality of the produce will be dictated by the quality of the soil. If a grower is looking to plant directly into the existing soil, a soil test should be completed to determine the specific make-up of the soil and the existing profile, and tailor any additions, fertilizers, or supplements accordingly. Generally, vegetables suitable for winter production grow best in soils with a pH between 6.0 and 7.0 (McCullough 1978, 267).

Soil is added before and after the harvest in low, raised beds. Typically, 6-10 inches are added to the raised beds during the first year of production. Throughout the growing season, the level will drop, and after the last plants are harvested, a few inches can be added to supplement the settling. Annual soil testing should occur to make sure that accumulated salts and minerals are at healthy levels for the types of plants to be grown.



Raised beds in a winter-only greenhouse at Elk's Bluff
Photo: Dan Handeen

Soil mixes are also particular to the types of plants intended for growth. The Northlands Winter Greenhouse Manual gives a recommendation for a soil mixtures that are specific to raised beds and planters and soil blocks (pages 44-45). **These mixtures contain ratios of peat moss (acidic, built-up partially decomposed vegetation used to retain moisture), vermiculite (superheated, expanded rock which adds micro-nutrients), compost (decomposing organic matter with high nutrient content), and organic fertilizer (composed of green sand, rock phosphate, and blood meal). Lime should be added to counteract the acidity of the peat moss.** Special attention should be paid to the source of the compost, to avoid introducing weed seeds, diseases, pests, or fungus into the greenhouse, where the elements of the outdoors (rain, wind, insects), which naturally regulate the soil outdoors, are absent.

It is important to maintain the optimum soil temperature throughout the season (winter-only greenhouse) and throughout the year (year-round greenhouse). Maintaining soil temperature is actually more important than maintaining air temperature for plant growth. **Optimal air temperature for growing in the cold-climate greenhouse is between 35°F and 75°F** (Coleman 1998, 57). Optimal soil temperature should be maintained around 50°F (McCullough 1978, 240) to avoid root freeze (which will slow growing or kill the plant when water is not able to be taken up by the roots). In a year-round greenhouse, overheating of the roots is a possibility, if the greenhouse is not properly ventilated to manage temperatures.

Additionally, the soil should be well-drained, whether growing directly into the ground or in trays. If excess moisture is allowed to build-up within the soil profile, especially at the surface of the soil, there is likelihood that freezing will occur when the air temperature drops within the greenhouse. Excess soil moisture can also lead to unwanted fungus or mold growth within the greenhouse.



Square Foot Garden with vermiculite, peat moss and compost
Photo: www.kingsalomon.net/wp-content/uploads/d010/04/box-for-square-foot-gardening-with-vermiculite-peat-moss-and-mushroom-compost.jpg

Greenhouse Frames

The type of structure used for a cold-climate greenhouse is largely dictated by the type of glazing used, the amount of time and money that the grower (or builder) is willing to put into the construction, and the degree of site-built modifications desired. Kits, which can be ordered through a variety of vendors, generally offer easier installation but may not be able to be modified easily on-site, nor will they be optimized for specific site conditions or winter growing. The following is a discussion of the pros and cons of the most common types of winter-use and year-round greenhouse structures used in the upper Midwest. Growers should contact their local building officials to find if and what is required in order to build structures in their municipality. Some areas may require licensed builders, or may have size restrictions for structures built by non-professionals.

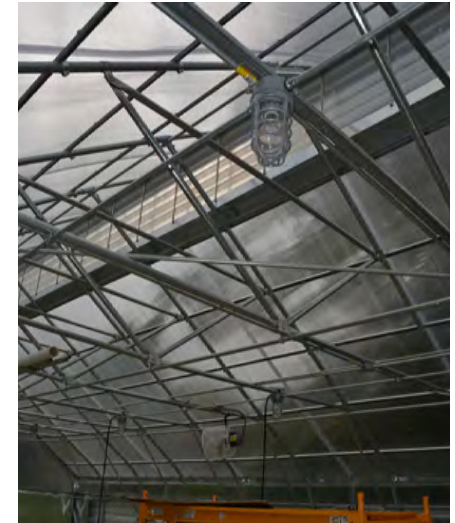
Metal Frame

Metal frame greenhouses are ubiquitous throughout the world as standard greenhouse structural material. Steel or aluminum frames can be ordered in standardized lengths and assembled on-site. Aluminum frames are generally less expensive, have longer life-span, and require little maintenance. Aluminum frames also have more light reflectance. Steel frames are heavier (and generally more expensive to ship), and must be painted or galvanized in order to resist moisture damage.

Metal frame structures pair well with polyethylene sheet glazing or polycarbonate panels, because the glazing can be attached directly to the exterior face of the frame. A wider span can be achieved through metal frame design (up to 40 feet, depending on the manufacturer's specifications), creating a larger and less-obstructed area for growing.



*(above) Aluminum frame quonset-style frame for high tunnels at Whitewater Gardens
Photo: Jody Rader*



*(right) Steel-framed trusses at Lanesboro High School
Photo: Jody Rader*

A benefit to using manufactured metal frame structures is that automatic ventilation systems can be integrated into the structure. The year-round greenhouses at Pork and Plants in Altura, MN demonstrates how a large-scale operation has successfully integrated frames made by United Greenhouses.

A drawback to using metal frame kits is that they are generally designed for conventional greenhouse use. A grower will need to work directly with the manufacturer or designer to customize a design to specify the glazing angle. Also, a kit will generally be designed to be a stand-alone structure, in either a gothic, gabled, or quonset design. If the grower intends to orient the greenhouse toward the south, this standardized style will likely need to be modified in order to attach to an existing building or a masonry wall, if this is desired.

Wood Frame + Mass Walls

The wood frame structures examined in this research were all site-built by the growers or by a contractor hired by the growers. Costs associated with wood frame structures vary, depending on the complexity of the design, the size of the greenhouse, and the materials sourced. Many growers have been able to use lumber milled from trees cut from their property, such as the black locust used in the greenhouse at Sweet Earth Farm.

Wood frame structures can be paired with any type of glazing (polyethylene, polycarbonate panels, or glass). The spacing of rafters (diagonal members) and the size is mainly dictated by the glazing material. Glass generally cannot span as far. Most of the greenhouses that were visited for this research that utilized wood framing had rafters every 24". Closer spacing of rafters will create shadows throughout the greenhouse, decreasing the solar gain. Painting the rafters white is common practice, in order to increase the amount of light that is reflected throughout the space.

Wood frame structures also are more versatile in design, as the material can be cut on site. Attaching a site-built greenhouse to an existing structure in the preferred direction may be easier, especially if the existing structure is also a wood-framed building.

Wood frame structures are susceptible to water and moisture damage. Sill plates of preservative-treated ('green-treat') wood are used by many growers, although some are wary of potential leaching of metals from the wood into the soil. Using rot-resistant wood species, such as cedar, especially for sill plates is recommended (Garden Goddess, 44).

Wood frames used in combination with a north-facing masonry or concrete wall is a very common style of structure found in smaller-scaled cold-climate greenhouses. If possible, building the mass

wall into a south-facing slope or berm is preferred (for absorbing and redistributing heat throughout the space). However, extensive excavation can be expensive, depending on the scope.

Mass walls are either cast-in-place concrete using formwork or Insulated Concrete Forms (ICF's), or are constructed using modular Concrete Masonry Units (CMU's). These walls should be continuously insulated (usually with rigid foam installed on the exterior of the wall). ICF's offer the convenience of providing both formwork and insulation in one step. Prior to pouring or setting of blocks, a plan should be made regarding the placement of any vents, electrical, plumbing, or mechanical components that will potentially be puncturing the wall.

Mass walls can be painted black to increase thermal absorbancy, or painted white to increase light reflectivity throughout the space.



(left) Painted wood frame structure with site-built trusses at Lorri Maus' greenhouse Photo: Jody Rader

(below) Poured-in-place concrete wall with wood frame at Sweet Earth greenhouse Photo: Jody Rader



Light/Glazing

Glazing is perhaps the single component which makes a greenhouse distinct from any other type of building. The purpose of the glazing is simple, yet there are many factors to consider when choosing the glazing type for the greenhouse. Primarily, the glazing should allow as much light to enter the greenhouse as possible. Solar energy enters the building envelope during the day, of which approximately 5% is used for photosynthesis (MacKinnon and Poisson). The remaining energy is either reflected back out of the greenhouse or enters as heat. This heat generally remains within the structure until the sun sets, when the absence of incoming solar energy causes the greenhouse to cool.

Generally, materials that allow more solar energy to enter the greenhouse during the day are also the same ones that allow more of it to escape during the night. Therefore, the insulating qualities of the glazing material, along with the assembly styles, are important for the year-round and winter-only greenhouse grower. Many glazing types take advantage of airspace as an insulator.

Factors to weigh are durability and cost, along with the compatibility with the structural system of the greenhouse. Hoop-houses generally use light-weight polyethylene sheets, tacked on to the structure (1-2" steel tubing). Generally, this material needs to be replaced every 3-4 years; damage from snow loads, strong winds, shrinking and expanding during seasonal changes, yellowing and UV rays can damage polyethylene sheets. However, the upfront cost is less than other materials, such as polycarbonate, which may last as long as 30 years, if installed correctly. Glass panels generally are the most transparent material but are most expensive (unless obtained through salvage). However, glass is more susceptible to damage during high-winds, more difficult to replace, and sometimes is unable to withstand heavier snow loads, similar to polyethylene.

Many advances in plastic technology have occurred over the last few decades. One of the biggest innovations has been to improve the texture of polyethylene sheets and other plastic-based materials so that condensation (which inevitably will accumulate as soon as the morning sun rises inside the greenhouse) does not drip down onto the plants (causing light transmission problems on leaves or contributing to disease within the closed system), and instead runs down the surface of the plastic. Condensation is especially a problem in greenhouses covered in polyethylene sheets. A simple way to reduce this is to use a double layer of polyethylene with an airspace between, reducing the difference between outdoor and indoor surface temperature on the plastic.

The following pages describe the most common material choices for glazing, along with commentary on the pros, cons, and general considerations. The technical information is provided by Barbara Bellows, an agricultural specialist at the National Sustainable Agriculture Information Service. This information has been reinforced by the testimonies of growers and the survey results performed for this research.

There are four numbers that may be found associated with greenhouse glazing materials; it is important to have an idea of what they mean, as this will help to determine the quality and performance advantages from one material to the other, and will 'level' the playing field between proprietary materials.

SHGC = Solar Heat Gain Coefficient

This is the amount of light which passes through the material. A SHGC of 0.60 or higher is preferable.


U-factor = the measure of the amount of heat that the material will transmit. (Here, a lower number is more desirable.) 0.35BTU/hr-ft²-F or lower is preferable. R-value is the inverse of the U-value. R-value is the measure of the insulating performance of the material. For R-values, a higher number is more desirable. An R-value of 2.85 or higher is preferable.

VT = Visible Transmittance

This is the amount of visible light that is able to pass through the material. A VT of 0.70 or higher is preferable.

PAR = Photosynthetically Active Radiation

This is the measure of the amount of sunlight needed for photosynthesis. Optimal PAR wavelength range is between 400-700 nanometers.

| | |
|---|--|
|  <small>national window rating center</small> Energy Star CERTIFIED | World's Best Window Co. <div>Millennium 2000® Vinyl Clad Wood Frame Double Glazing • Argon Fill • Low E Product Type: Vertical Slider</div> |
| ENERGY PERFORMANCE RATINGS | |
| U-Factor (U, U-F, P) | Solar Heat Gain Coefficient |
| 0.35 | 0.32 |
| ADDITIONAL PERFORMANCE RATINGS | |
| Visible Transmittance | Air Leakage (U, U-F, P) |
| 0.51 | 0.2 |
| Condensation Resistance | — |
| 51 | |
| <small>NFRC labels are based on the data provided by the manufacturer and are not intended to be used for comparison purposes. NFRC labels are not intended to be used for comparison purposes. NFRC labels are not intended to be used for comparison purposes. NFRC labels are not intended to be used for comparison purposes.</small> | |

Typical National Fenestration Rating Council (NFRC) label on residential windows describing performance characteristics
 Photo: Environmental Protection Agency

Glass

Glass is typically found in greenhouses built prior to 1990, or in smaller-scaled greenhouses (residential-style) that are site-constructed. The growers interviewed who used glass as a primary glazing material acknowledged that glass is expensive. However, most were able to secure salvaged windows from other projects, or secured donated glass. The aesthetic appeal to using glass is understandable, as glass has a familiar and permanent connotation. This may be a good material to choose for a greenhouse that will be used for educational purposes, as ‘curb appeal’ in these greenhouses can lend itself to funding sources.



*Salvaged Double-paned glass at Sweet Earth greenhouse
Photo: Harriet Behar*

Single Pane

Light transmission: 85-90% BEST (percentage of solar energy that is usable within the greenhouse, as compared to the total amount possible)

R-value: 0.9 LOW (measure of the ability of the material to resist heat transfer)

Pros: Will not show signs of ‘wear’, if tempered, will be able to span longer, reducing the amount of framing necessary, is generally more aesthetically pleasing and looks more permanent than other materials

Cons: Fragile—easily broken during winter storms, light quality is direct, never diffused (unless a coating is applied to the surface), expensive (unless found salvaged, which may be difficult to replace), may be difficult to install.

Double Pane (factory sealed)

Light transmission: 70-75%

R-value: 1.5-2.5

Pros: Will not show signs of ‘wear’, if tempered, will be able to span longer, reducing the amount of framing necessary, is generally more aesthetically pleasing and looks more permanent than other materials, has much better insulating value than single-pane glass

Cons: Fragile—easily broken during winter storms, light quality is direct, never diffused (unless a coating is applied to the surface), expensive (unless found salvaged, in which case it is difficult to replace broken windows), may be difficult to install.

Polyethylene

Polyethylene sheets are typically found in high-tunnel styled greenhouses. While associated with more temporary structures, many growers, such as Whitewater Gardens and Pork and Plants (both in Altura, MN) use polyethylene sheets for their large-scale, permanent greenhouse operations. With very tight installation, the polyethylene sheets at Pork and Plants have lasted for over 13 years. Generally, the sheets need to be replaced every 3-4 years, due to weathering and yellowing. This is a material that is commonly paired up with a very simple (and minimal) framing system (1-2" steel tube frame). Careful installation is important, as the material is prone to tearing. This material will expand during the warm summer months, and contract during the cold time of the year. This is one of the more reasonably priced options for greenhouse glazing. This material's properties can be improved by using double layers with airspace between.



Greenhouses and hoophouses with polyethylene glazing at Womens' Environmental Institute Photo: Jody Rader



Double 6mil polyethylene glazing at Whitewater Gardens Photo: Jody Rader

Single Layer

Light Transmission: 80-90% (if new)

R-Value: 0.87

Pros: Films can be applied to the sheets to reduce condensation, if treated with ethyl vinyl acetate will result in resistance to cracking and tearing, easy to install, low cost.

Cons: Does not wear well, translucent (not transparent), UV resistance wears and light transmission increases over time, expands and contracts with change in seasons, can be somewhat unattractive, prone to collapse during heavy snow loads

Double Layer

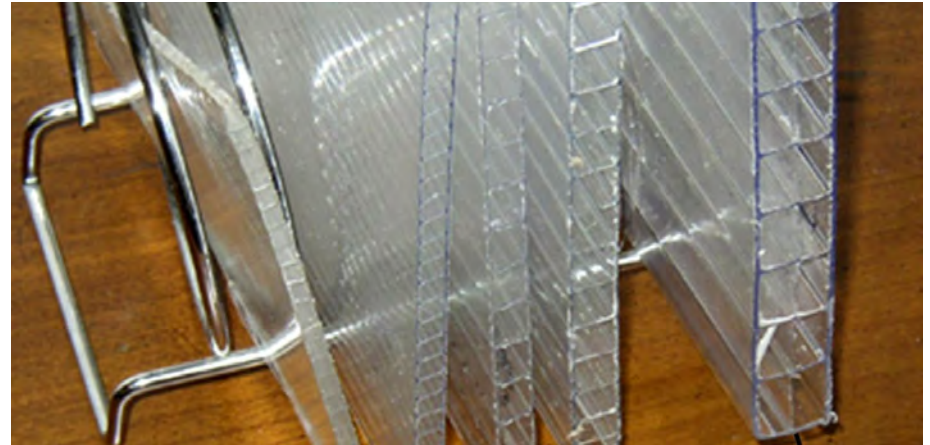
Light Transmission: 60-80%

R-value: 1.5-1.7 (without airspace)

Pros: Can increase R-value if a blower is used to create an airspace, Films can be applied to the sheets to reduce condensation, if treated with ethyl vinyl acetate will result in resistance to cracking and tearing, easy to install, low cost.

Polycarbonate

Today, Polycarbonate is one of the most widely used glazing materials (in greenhouses). This rigid material performs well in areas prone to heavy snow loads and wind loads, while being very lightweight and also easy to install. The material is available for purchase for custom cutting and use on-site, and is also used in greenhouse kits. This is a versatile material; if skillfully installed, can last for up to 10-12 years (depending on the manufacturer). Options include double-walled and triple or quad-walled; increasing the number of wall layers increases the R-value, although decreasing the amount of light transmission.



*Various thicknesses of twin wall and triple wall polycarbonate panels
Photo: site.outdora.com*

Double Wall

Light Transmission: 83%

R-Value: 1.4-1.8

SHGC: 0.77

VT: 82

Pros: Fire-resistant, high structural performance, easy to install, longer-lasting than polyethylene sheets, UV resistant

Cons: Translucent (not transparent), expensive

Triple/Quad Wall

Light Transmission: 75%

R-Value: 2-4.1 BEST

SHGC: 0.33-0.59

VT: 15-74

Pros: Fire-resistant, high structural performance, easy to install, longer-lasting than polyethylene sheets, UV resistant, higher R-value than double-walled

Cons: Translucent (not transparent), expensive



*Full-height 12' polycarbonate panels attached to wood frame
at Lorri Maus' greenhouse Photo: Jody Rader*

Heat — Keeping the Greenhouse Warm

Heating the cold-climate greenhouse during the winter months is a challenge that is met with varied solutions and combinations of solutions by growers in the Midwest. Depending on what is being grown, optimal growing temperatures range from 35°-85°F. During a sunny winter day, when the sun is shining through the glass or plastic glazing, this is not difficult, even if the outside temperatures are below freezing. However, these temperatures cannot be sustained during the nighttime or on cloudy days without employing a variety of methods. The conventional method of heating a greenhouse in Zones 4 or 5, typically propane-burning forced air heaters, can be extremely costly and inefficient. Most growers depend on a variety of primary and secondary heat sources and heat storage solutions to maintain optimal temperatures for growing. Most cold-climate greenhouse growers also keep a back-up conventional heater on hand for when primary heating methods are unable to keep up with extreme temperature drops.

There are many conventional and alternative heating methods being used by growers across the country, and this list is not exhaustive. However, this reflects the successful and efficient strategies employed by growers across the Midwest who were interviewed for this project.



Wood-burning rocket stove at Whitewater Gardens Photo: Jody Rader

Passive Solar: Heat Storage

The most basic method for maintaining temperatures in the cold-climate greenhouse is to utilize heat storage methods. Solar heat is absorbed by thermal mass materials like concrete, bricks, ceramic tile, water, and soil during the day. When the air temperature drops during the evenings, the heat stored in these materials radiates back out, regulating the temperature inside the thermal envelope. For these materials to be effective, they should be located in direct sunlight for as long as possible throughout the day, while avoiding contact with any uninsulated exterior glazing or walls.

Water is commonly used for heat storage. 55-gallon barrels filled with water can be placed in areas of direct sun (generally along the north wall of the greenhouse, doubling as a long table for holding trays of plants). These barrels should be a dark color, to assist with heat absorption. Smaller containers can be used (low-tech solution: milk jugs), which increase the amount of heat absorbed by the water because of the greater surface area. However, these will likely need to be replaced after a few years because the plastic will degrade with exposure to UV rays.

If using water as a heat storage method is the only means for heating a cold-climate, it is suggested to try to use at least 4 gallons of water per square foot of south-facing glazing. Depending on the size and shape of the greenhouse, however, using water as heat storage will take up far too much valuable space within the greenhouse. Similarly, masonry walls can be used to store heat. If solely relying on masonry as a heat storage device for maintaining optimal temperatures, it is suggested to have at least 3 square feet (4" thick) of masonry surface for every square foot of south-facing glazing. (Alward and Shapiro, 1980)

Generally, heat storage methods are used in combination with other

methods. Growers in Zones 3 or 4 will have a difficult time finding enough space within their greenhouses to adequately use only heat storage as a means of maintaining optimal temperatures. Surfaces that are intended to be used for heat storage should be dark colors or painted so. **However, in general, walls and other surfaces within the greenhouse not intended for heat storage should be painted white, as they will better serve the greenhouse as reflectors of light during the day.**



55-gallon barrels serving as thermal mass & work surface at Garden Goddess Photo: Jody Rader



Milk jugs filled with water at Lorri Maus' greenhouse Photo: Jody Rader



Thermal mass integrated into storage at Paradox Farm (in construction) Photo: Sue Wika

Active Solar or Subterranean Heating

An efficient means of maintaining heat in a cold-climate greenhouse is through a form of solar heat storage known as subterranean heating. Hot air, which rises to the top of the greenhouse during the day, is captured at the ridge or top of the greenhouse structure. It is then directed down below the soil surface and distributed through a series of ducts that run through a bed of rocks. The rocks store the heat, and radiate it to the soil above during the nighttime hours.

Generally, the rock bed should consist of river rock, with diameters of 1.5-2 inches, in order to maximize the surface area for heat storage. It is important that airspace is maintained between the rocks for air flow, so no fines should be allowed in the rock bed that could clog the airspace or the perforations in the drain tile. The rock bed should be approximately 2 feet below the surface of the soil (if growing directly in the soil), and deep enough to cover the drain tile at least 4" below and above.

It is best to use corrugated, perforated drain tile (most growers use 4" diameter) within the river rock. The corrugation in the tile will provide more surface area for heating the rocks around it. Based on testimony from growers interviewed for this research, the more drain tile that is installed, the better. This method of heating within the greenhouse can raise average soil temperatures 10-15 degrees during the coldest time of the year, and can really make a difference in the survival of winter produce grown directly in the ground. A minimum amount of drain tile to be installed for this type of heating system would be the equivalent surface area of the drain tile to the surface area of the greenhouse. So, the total length of the drain tile should be approximately half of the floor area of the greenhouse.

It is important that the fan used to pump the solar heated air provides

adequate airflow. Successful systems use a fan that provides at least five air changes per hour. This rule of thumb is compatible with subterranean heating and cooling systems developed by the Colorado Rocky Mountain Permaculture Institute (www.crmipi.org/) and explained by Going Concerns Limited (<http://www.sunnyjohn.com/indexpages/shcs.htm>).

The subterranean system works best with an automated temperature controlled system, set to turn the fans on when the air temperature at the top of the greenhouse reaches approximately 20 degrees F above the temperature at the soil surface.



***Subterranean heating system (under construction) at Elk's Bluff
Photo: Chuck Waibel***



***Hot air is drawn into black ductwork
(upper R) at Garden Goddess
Photo: Jody Rader***

Alternative Fuel and Heat Sources

As mentioned earlier, most growers utilize a combination of passive and active heating methods, with conventional forced air systems or radiators kept as back-up for days with extremely low temperatures. Additionally, some growers use conventional delivery systems as their primary heat source, albeit with alternative fuel sources or alternative heat sources.

Eric Kriederman, owner of Pork and Plants, in Altura, Minnesota, has perfected a hydronic system of in-floor slab heating in his year-round greenhouse, using pelletized biomass as fuel. Additionally, tables for starter plants are heated with the same hydronic system. The pellets are produced locally with prairie grasses and other biomass, and have proven to be a cost-effective and highly efficient system.

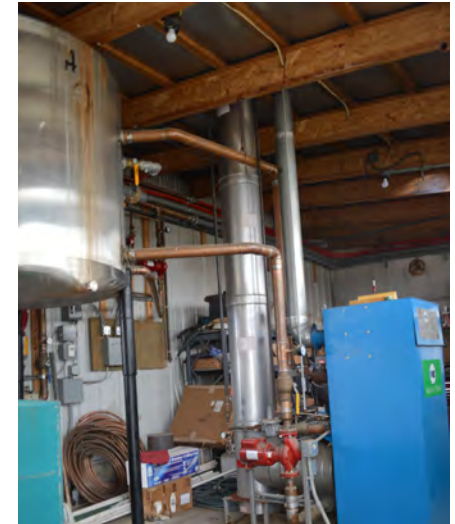
Lonny and Sandy Dietz of Whitewater Gardens installed an extensive ground-sourced geothermal heating system to heat their greenhouse, along with a number of other buildings within their farm. This system had high installation costs, compared with other growers interviewed for this project.

While a wood-burning stove is not 'alternative', it is also not very common to find these days, especially in a greenhouse. However, Harriet Behar utilizes a wood-burning stove for her 1,200 sf winter-use greenhouse as a means to supplement the subterranean heating system. She claims to only use the stove for her own comfort to heat the greenhouse while she works tending to the produce. Over the course of a typical winter, she burns through a cord of wood, which costs approximately \$60.

Any forced air or radiant systems should be placed far enough away from plants to avoid burning, and should be distributed throughout the greenhouse to avoid over-heating or under-heating of particular areas.



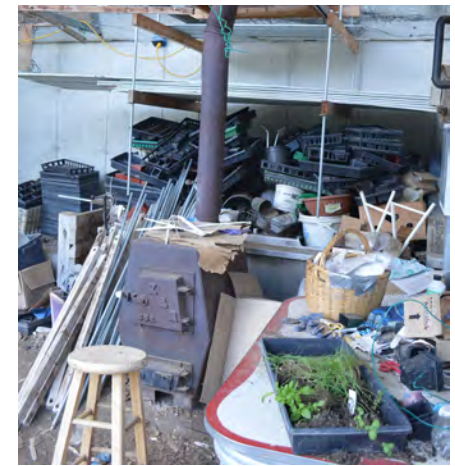
Geothermal Heating System at Whitewater Gardens
Photo: Jody Rader



Boiler System with pelletized biomass fuel at Pork and Plants
Photo: Jody Rader



Wood stove at Whitewater Gardens
Photo: Jody Rader



Wood-burning stove at Sweet Earth Farm Photo: Jody Rader

Ventilation

The importance of greenhouse ventilation cannot be stressed enough. Many growers reported underestimating the necessity for properly sized, sealed, and functioning ventilation systems. As a result, the air temperatures in the greenhouse fluctuate too widely, shocking the plants, and causing damage. Additionally, plants need constant supply of CO₂ in order to grow, as well as humidity regulation. Ventilation is a key component to any greenhouse, whether it is a conventional operation, season extension, or winter-use only.

It should be noted, however, that winter-optimized greenhouses do not require excessive ventilation rates, as their use in summertime, when overheating would occur, is minimal. In addition, the steep pitch of the south facade helps to reject summer solar heat gain, as the angle of incidence is such that most light and heat from the high summer sun is reflected rather than allowed into the space.

To achieve adequate ventilation in overheating periods, a surface area of 1/5 to 1/6 of the floor area should be dedicated to ventilation. (www.illinoissolar.org/) This can be a combination of ridge and gable end vents. Louvered vents should incorporate a bug screen to minimize pest intrusion.

Ridge vents worked better than gable end vents, according to the growers interviewed for this report. Additionally, automated venting systems controlled by temperature sensors, are highly preferred to maintain proper air temperatures throughout the day. The Pork

and Plants greenhouse is an excellent example of an automatic ventilation system that works extremely well. The entire roof structure of the aluminum-frame greenhouse opens and closes automatically, keeping the air temperatures and flow within the structure to optimal levels. Essentially a series of gabled roofs that open at the ridges, the whole system will automatically shut when it rains.

Another innovative ventilation strategy is found at Harriet Behar's greenhouse. Here, she integrated cold frames at the exterior southern edge of the greenhouse, which can be opened fully. When used in combination with the automated ridge vent system, the year-round greenhouse stays cool during the summer, and adequately vented during the colder months.



Ridge ventilation at Sweet Earth Farm Photo: Jody Rader



Full roof ventilation at Pork & Plants Photo: Dan Handeen

Operable Insulation

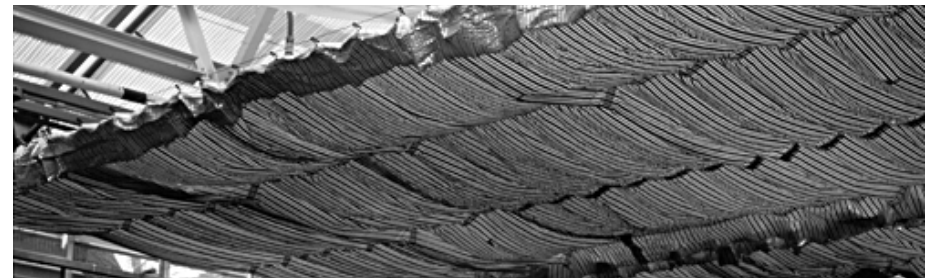
Insulation throughout the cold-climate greenhouse will improve the performance of the building and help keep the space cool during the summer and warm during the winter. All surfaces that are not intended for heat absorption or glazing should be insulated as much as possible, although this does not account for very much surface area throughout the greenhouse. The following are two examples of operable insulation strategies which attempt to add insulation performance to glazed areas.

As discussed earlier in the glazing section, utilizing an airspace between layers of polyethylene or between walls of polycarbonate will contribute to the insulating performance of the greenhouse. An innovative product called Poly Vent, developed by Poly-Tex, has been installed at two high school educational greenhouses in southeast Minnesota (Chatfield High School and Lanesboro High School). These greenhouses integrate twin wall polycarbonate panels for glazing in combination with 6mil polyethylene tubular-celled sleeves for walls and ridge vents. The sleeves inflate and deflate, controlled automatically through temperature sensors. When the sleeves are inflated, the walls are completely sealed with up to 3 inches of airspace that serves as insulation. When the sleeves are deflated, the panels open up to provide ventilation. This system works as both ventilation and insulation, although the functions are exclusive. This system works with a tubular kit structure, and has relatively high up-front costs. At the time of this research, the performance of these greenhouses had not been tested or documented through the winter. (www.poly-tex.com)

Although rarely used by growers in the upper Midwest, there is significant research which supports the value of operable insulating blankets within cold-climate greenhouses (Roberts et al), as up to 85% of heat loss occurs at night (Latimer, 2009). These blankets

can be rolled up (either manually or automatically) during the day on rollers, and can be made of a variety of materials. A low-tech approach to operable insulation is to manually install rigid foam sheets on the interior of the glazing at dusk, secured by friction fit or Velcro. This method is not practical if there is no storage area within the greenhouse, or labor to put up every night and remove in the morning.

Although not operable, some key methods for insulating the greenhouse include thoroughly sealing all joints and cracks throughout the walls, ceilings, doorways, and vents with caulk and weatherstripping.



Thermal blankets

Photo: Joyce G. Latimer Virginia Cooperative Extension



*Poly-Vent air compressor at Lanesboro High School
Photo: Jody Rader*



*Poly-Vent sidewall ventilation/insulation at Lanesboro High School
Photo: Jody Rader*

Irrigation

Most of the growers interviewed for this research had well-water pumps installed at the time of greenhouse construction. A variety of manual watering, misters, drip irrigation, and automated systems are used in cold-climate greenhouses. Whether to choose automatic or manual irrigation systems is purely dictated by the amount of available labor and the size of the greenhouse. For the smaller operations, with only 1-2 people working within the greenhouse at any given time, approximately 2-6 hours are required to spend manually watering the greenhouse plants during the winter months.

Innovative examples of irrigation techniques were demonstrated at Pork and Plants year-round greenhouse. First, an underground cistern (installed at the time of construction) stores all of the rainwater collected from the runoff from the roof of the greenhouse. This water is pumped up to individual holding tanks (shown in the lower middle in the photo to the right), located at the ends of each bay of movable tables.

On a daily schedule, one of the employees walks through the greenhouse and switches the valve on the holding tanks to allow water to be pumped onto tables, each of which is essentially a large, shallow trough. The plants sit in biodegradable trays on the tables and are irrigated through the roots as the trough on the table fills. After the roots are saturated, the excess water is drained back into the holding tanks. Overhead misters supplement this irrigation method for starter plants.



Flood table system at Pork and Plants Photo: Dan Handeen

Interior Layout

Prior to construction, determine an approximate horizontal and vertical arrangement for the greenhouse, with care taken to ensure access for watering and harvesting. To maximize efficiency, every possible area for growing should be used (if production is a priority). This generally means using a combination of horizontal and vertical storage and planting solutions.

Taller and larger plants should be placed towards the back (north) of the greenhouse, with shorter plants towards the south, to avoid shading of plants within the greenhouse.

Hanging trays have become a popular element of greenhouse design, as they can contribute additional growing area. Tender and hardy greens can be grown in these, which can be easily constructed out of rain gutters with holes drilled into the bottom. The benefit of growing in the gutters is that the raised heights can make harvesting and watering easier. Also, hanging trays can be more mobile; plants can be moved throughout the greenhouse to areas that are warmer or cooler, depending on their needs. Many growers integrate the hanging trays into the structural system of the greenhouse, using horizontal rafter supports as a way to hang trays. Harriet Behar uses swiveling hangers which add to the versatility of the greenhouse arrangement, as she can move the trays as she works throughout the greenhouse.

Sue Wika with Paradox Farms has built a unique greenhouse based on the Garden Goddess design. At the Paradox Farms greenhouse, a lofted area was built high into the north wall. Here, fodder (in trays) is grown to supplement livestock diets throughout the winter. (Photo at upper right).

Often, growers will stack trays of starter plants toward the back or against a side wall, on shelves or tables (sometimes over thermal-storage barrels of water). As the plants mature, they are transferred to the main growing area, either in the ground, in containers or trays, or on tables within the greenhouse. Then they are harvested, or possibly transplanted to an exterior garden.

Rolling tables can save space within the greenhouse, only one aisle at any given time is taking up space within the greenhouse. However, moving tables can be cumbersome if more than one person is working in the greenhouse at a time.

In general, interior layouts should consider both the grower's comfort and accessibility throughout the greenhouse while providing as much space as possible for growing and production.



Hanging trays Photo: Sue Wika



*Lofted fodder arrangement
Photo: Sue Wika*



*(right) Rolling tables at Badgersett
Research Farm Photo: Jody Rader*



appendix

Greenhouse Profiles (pg. 43-47)

Profile pages highlighting selected growers and their greenhouses. These projects were documented through visits and interviews over the summer of 2013 and demonstrate a variety of successful operations.

Links and Resources (pg. 48)

A list of web-based resources for further research of passive solar/cold climate greenhouses.

Survey Results (Pg. 49-62)

Graphic representation of survey results gathered through an online survey administered over the summer of 2013.

**Sweet Earth Farm
Gays Mills, WI
Harriet Behar**



Earth-Bermed Passive Solar Year-Round Greenhouse

Products: Spinach/lettuce/beets in winter, cucumbers, tomatoes, eggplant in summer, herbs and starter plants

Primary End-Users: Retail

Greenhouse Growing Season: Year-round

Cost to Build: \$50,000 (\$41.67/SF)

Heat Source: Passive solar, wood-burning stove

Heat Storage/Delivery: Hot air captured from ridge of greenhouse and piped into bed of river rock, beneath the soil

Heat/Utilities Annual Cost: 1/2 cord of wood (approx. \$60); photovoltaic solar panels provide electric power to run supplemental lighting in the greenhouse

Glazing Material: Double-paned insulated glass (salvaged)

Ventilation: Automatic ridge vent with manually operated cold-frame louvers

Irrigation: Overhead misters

Structure: Poured masonry wall embedded in a south-facing slope with 2x rafters (Black Locust harvested from the farm property)

Dimensions: 20'x60'

Orientation: East-West

Coordinates: 43 deg. north, 91 deg. west

Built in 2001, Harriet Behar has created a very successful year-round passive-solar greenhouse that is modeled after Anna Edey's Solviva greenhouse design. Harriet has perfected an annual schedule of production which integrates plants grown in-ground, hanging trays, cold-frames, and starter plants, some of which are moved to or from a hoop-house or outdoor crops. The simple design and carefully crafted structure maintains both warm temperatures throughout the winter and cooler temperatures during the summer.

**Garden Goddess
Milan, MN**

Chuck Weibel & Carol Ford

<http://gardengoddessnetwork.ning.com/>

Garage-Attached Passive Solar Greenhouse for 12-share CSA



Products: Tender and hardy greens

Primary End-Users: 12-share CSA and family/friends

Greenhouse Growing Season: Early Fall through Spring

Cost to Build: \$18,000 (\$51.14/SF)

Heat Source: Passive Solar, back-up LP heater

Heat Storage/Delivery: Hot air captured from ridge of greenhouse and piped into bed of river rock, beneath the soil

Heat/Utilities Annual Cost: \$100 (\$3.52/SF)

Glazing Material: 8mm twinwall polycarbonate panels

Ventilation: (2) small fans and a gable vent

Irrigation: Manual

Structure: 2x stick-framed lean-to attached to garage, which serves as a packing and storage shed

Dimensions: 16'x22', 13' at tallest height with 45 deg. glazing wall

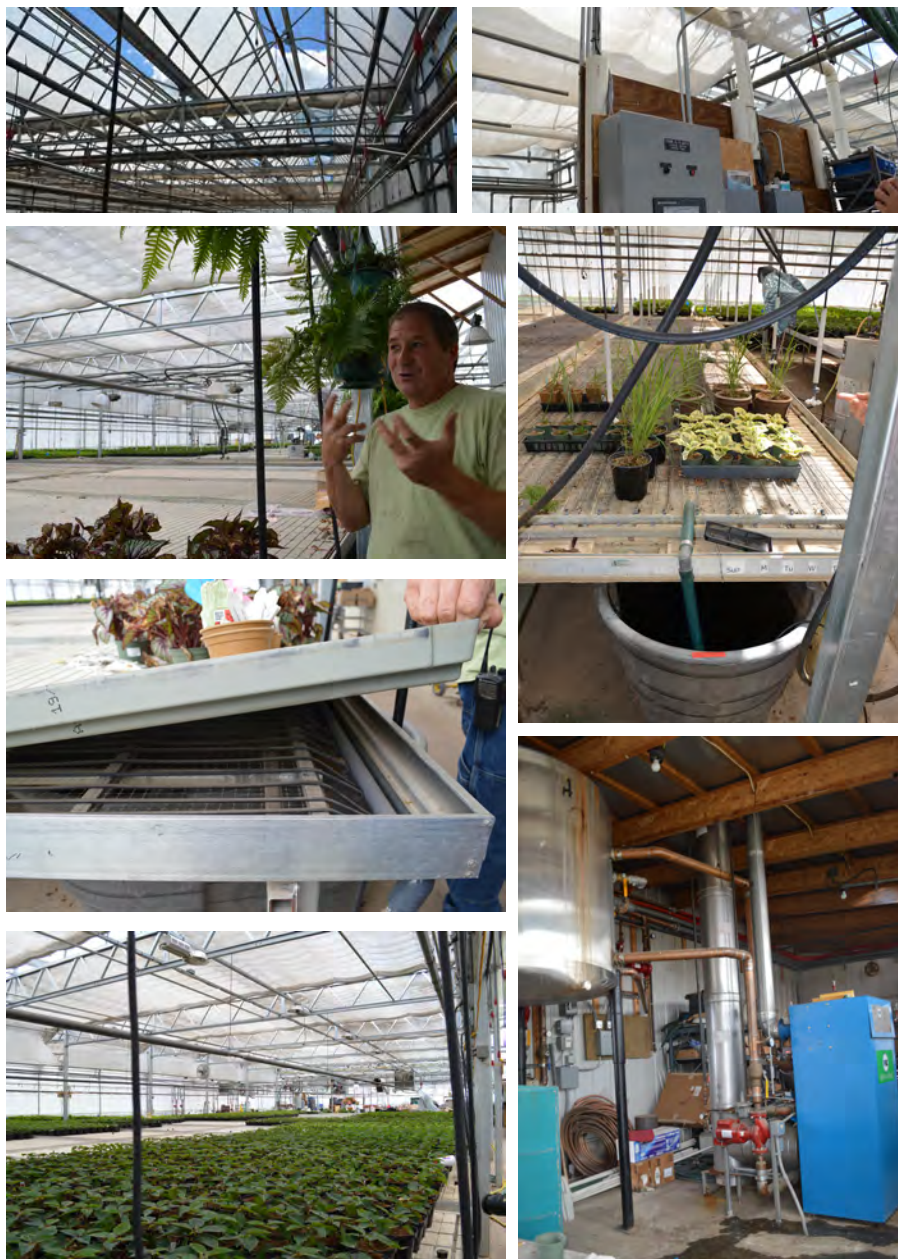
Orientation: East-West

Coordinates: 45 deg. north, 96 deg. west

Chuck Waibel and Carol Ford have jumpstarted the cold-season greenhouse movement in the upper midwest with the publication of *The Northlands Winter Greenhouse Manual* (Garden Goddess publications, 2009).

The book clearly describes the path that they took in the design and construction of their greenhouse, and provides many helpful guidelines and considerations. Also included is a comprehensive list of the crops, cultivation, and marketing that they have undertaken.

Pork and Plants
Altura, MN
Kreidermacher Family
<http://www.porkandplants.com/>



Large-scale Retail Greenhouse

Products: House and garden plants; to start vegetables in the future

Primary End-Users: Retail customers

Greenhouse Growing Season: Year-round

Cost to Build:

Heat Source: Radiant hydronic system, burning pelletized, locally-sourced biofuel; back-up LP hydronic system and LP forced air heaters.

Heat Storage/Delivery:

Heat/Utilities Annual Cost: \$100 (\$3.52/SF)

Glazing Material: double 6mm polyethylene sheets (inflated)

Ventilation: Fully-automated louvers (fully-integrated into roof structure).

Irrigation: Flood tables supplied by rainwater collected from greenhouse roof.

Structure: (4) gutter-connected steel-frame gothic-style greenhouses with fully-operable roof structure for ventilation (United Greenhouses)

Dimensions: 109'x ? (total)

Orientation: North-South

Coordinates: 44 deg. north, 92 deg. west

Pork and Plants is a large operation that focuses on the propagation of potted plants for retail sale. Pork and Plants produces their own pelletized biomass fuel, and heats the greenhouses by burning the pellets to heat water which is then piped through the greenhouses.

Unique among the greenhouses studied, the roof panels of the Pork and Plants greenhouses open up almost completely to provide ventilation without any fan power.

Whitewater Gardens Farm
Altura, MN
Lonny and Sandy Dietz
<http://www.facebook.com/pages/Whitewater-Gardens-Farm/349854475789>

Hoop-House Style Greenhouse with Geothermal Heat System

Products: Tomatoes, ginger, ghost peppers, cucumbers

Primary End-Users: Retail sales, wholesale, CSA, farmers' market

Greenhouse Growing Season: Year-round

Cost to Build: \$150,000 (structure + geothermal system for multiple buildings)

Heat Source: Geothermal heat pump, (2) back-up 300k BTU LP heaters

Heat Storage/Delivery: Heat pump provides warm air to the soil, while the back-up systems circulate warm air above the soil

Heat/Utilities Annual Cost: \$15,000

Glazing Material: double 6mm (4-yr) polyethylene sheets

Ventilation: Combination of manual door openings, automatic louvers and fans

Irrigation: Automatic dripline

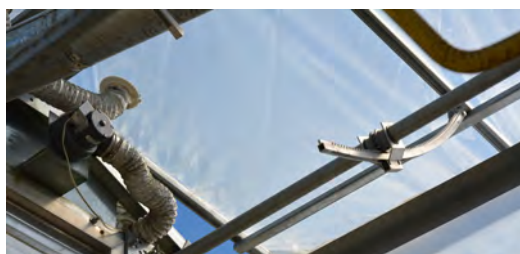
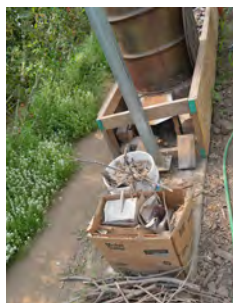
Structure: (2) Bay, gutter-connected hoop-house style greenhouse with steel frame

Dimensions: 46'x126' with 9' kneewalls

Orientation: North-South

Coordinates: 44 deg. north, 92 deg. west

Whitewater Gardens uses three geothermal heat pumps to heat their greenhouses. Heat is circulated through the soil via tubes of heated water. They concentrate on growing heat-loving plants such as tomatoes, cucumbers, and ginger year-round, thus the heating demands are quite significant.



King Gardens
Longville, MN
John Sumption

<http://www.kinggardens.com/>

Season Extension Passive Solar Heated Soil High Tunnel

Products: Hardy greens, tender greens and tomatoes

Primary End-Users: Retail sales, 30-member CSA

Greenhouse Growing Season: Mid-February to December 1st

Cost to Build: \$8,200 total (structure + passive soil heat system)
(\$3.80/SF)

Heat Source: Passive solar

Heat Storage/Delivery: forced air subsurface soil heat

Heat/Utilities Annual Cost: \$60 to run fan only (\$0.03/SF)

Glazing Material: single layer 6mm polyethylene sheets

Ventilation: Manual door opening and roll-up sides

Irrigation: Automatic dripline

Structure: 1.75" dia. steel tubular hoop house structure (FarmTek kit)

Dimensions: 30'x72' (2,160 SF)

Orientation: East-west

Coordinates: 47 deg. north, 94 deg. west

The King Gardens greenhouse uses a sub-surface network of ductwork to distribute captured solar heat to the soil contained within a large hoophouse.



Links and Resources

Midwest Season Extension

<http://www.midwestseasonextension.org/>

Four Season Farm: Barbara Damrosch & Eliot Coleman

<http://www.fourseasonfarm.com/>

MOSES – Midwest Organic and Sustainable Education Service

www.mosesorganic.org/

Build It Solar: The Renewable Energy site for Do-It-Yourselfers

www.builditsolar.com/

By Example: The Quest for Sustainable Living, Plans for A Passive Solar Greenhouse

byexample.com/projects/current/passive_solar_greenhouse_plans/index.html

Digging in the Driftless: Life among the weeds in Western Wisconsin

digginginthedriftless.com

Cooking Up a Story: A Show About Sustainable Living,

Thermal Banking: Cold Storage (video)

<http://cookingupastory.com/thermal-banking-for-cold-storage>

Garden Goddess Network: Home of the Deep Winter Producers' Association

<http://gardengoddessnetwork.ning.com/>

Solar Cold Climate Greenhouse (SCCG)

<http://www.mwt.net/~roald/solargh.html>

The “Green” Greenhouse

<http://people.umass.edu/~caffery/greenhouse/index.html>

National Sustainable Agriculture Information Service

<https://attra.ncat.org/other.html#University>

Center for Integrated Natural Resources and Agricultural Management

<http://www.cinram.umn.edu/about/index.html>

Minnesota Institute for Sustainable Agriculture

<http://www.misa.umn.edu/>

The Seed Hopper: Winter Farming in Southwest Montana

<http://www.highmowingseeds.com/blog/winter-farming-in-southwest-montana/>

The Farm at St. Joes: Growing a Healthy Community

<http://stjoefarm.wordpress.com/>

Solar Greenhouses, L. David Roper

<http://www.ropeld.com/>

Central rocky Mountain Permaculture Institute

<http://crmpi.org/>

The Solar Greenhouse That's Right for You (MacKinnon and Poisson)

Survivalplus.com/foods/The-Solar-Greenhouse.htm

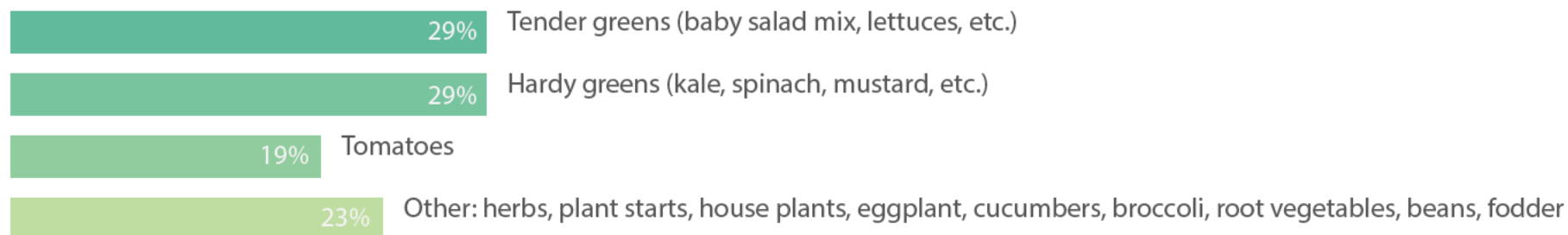
Integrated Pest Management, Greenhouse Crops and Floriculture Program, UMass Amherst Extension

umass.edu/floriculture/greenhouse-best-management-practices-bmp-manual/integrated-pest-management

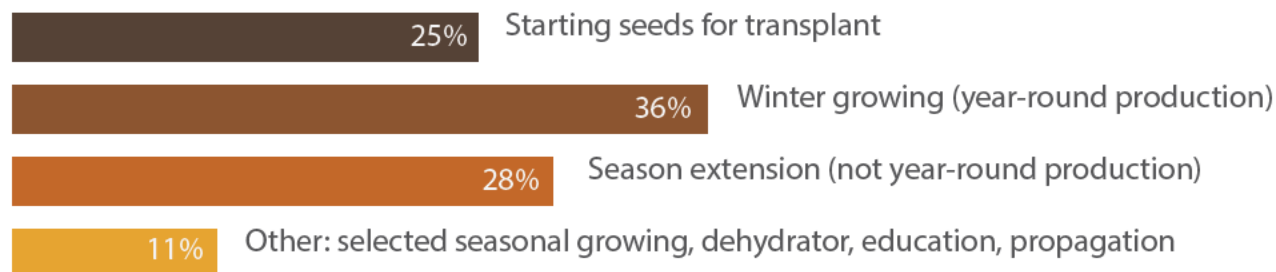
Survey Results

The following are graphic representations of the results gathered through the online survey, administered during the summer of 2013. Thirty-three greenhouse growers participated in this valuable research.

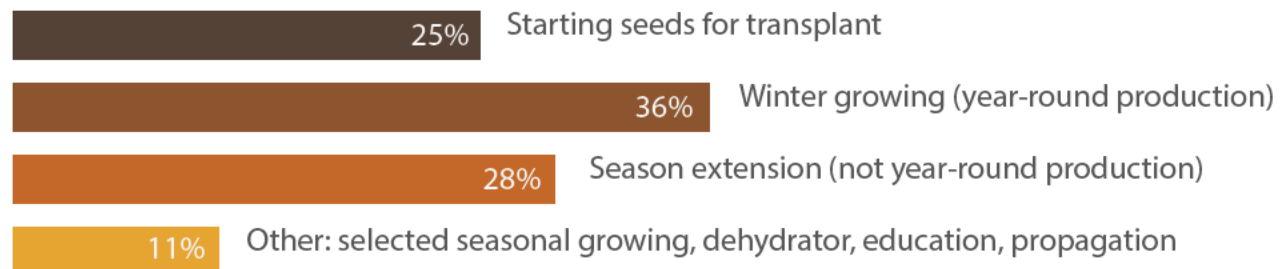
What do you grow?



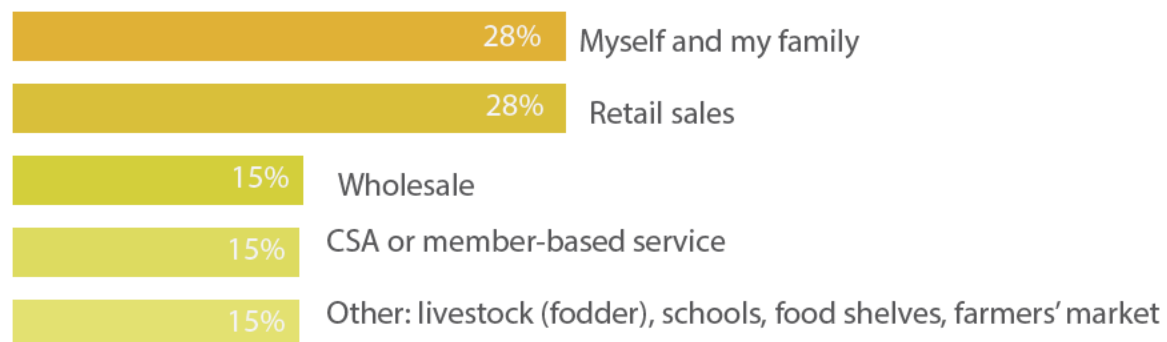
What is the primary function for your greenhouse?



What is the primary function for your greenhouse?

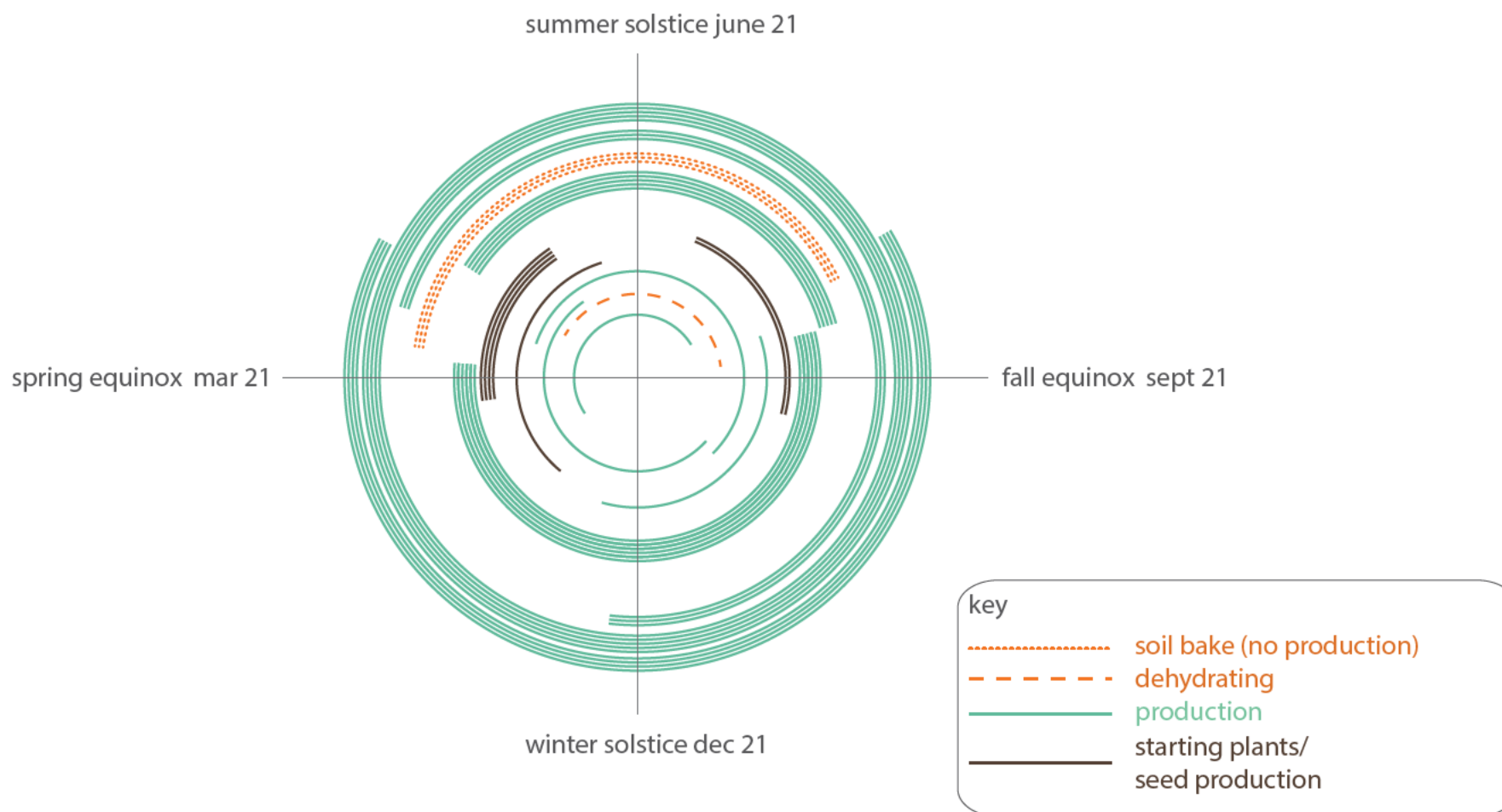


Who are the primary end users of production from the greenhouse?

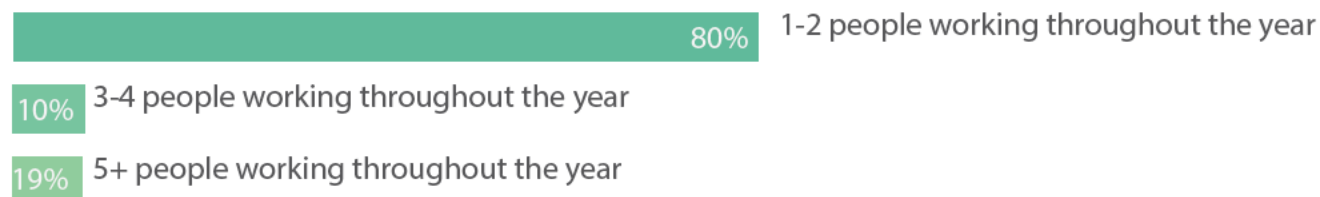


How does the use in your greenhouse change throughout the year?

Each arc represents a period of time, as reported by survey respondents. Most growers utilize their greenhouse in multiple ways throughout the year. Five respondents reported production throughout the entire year.

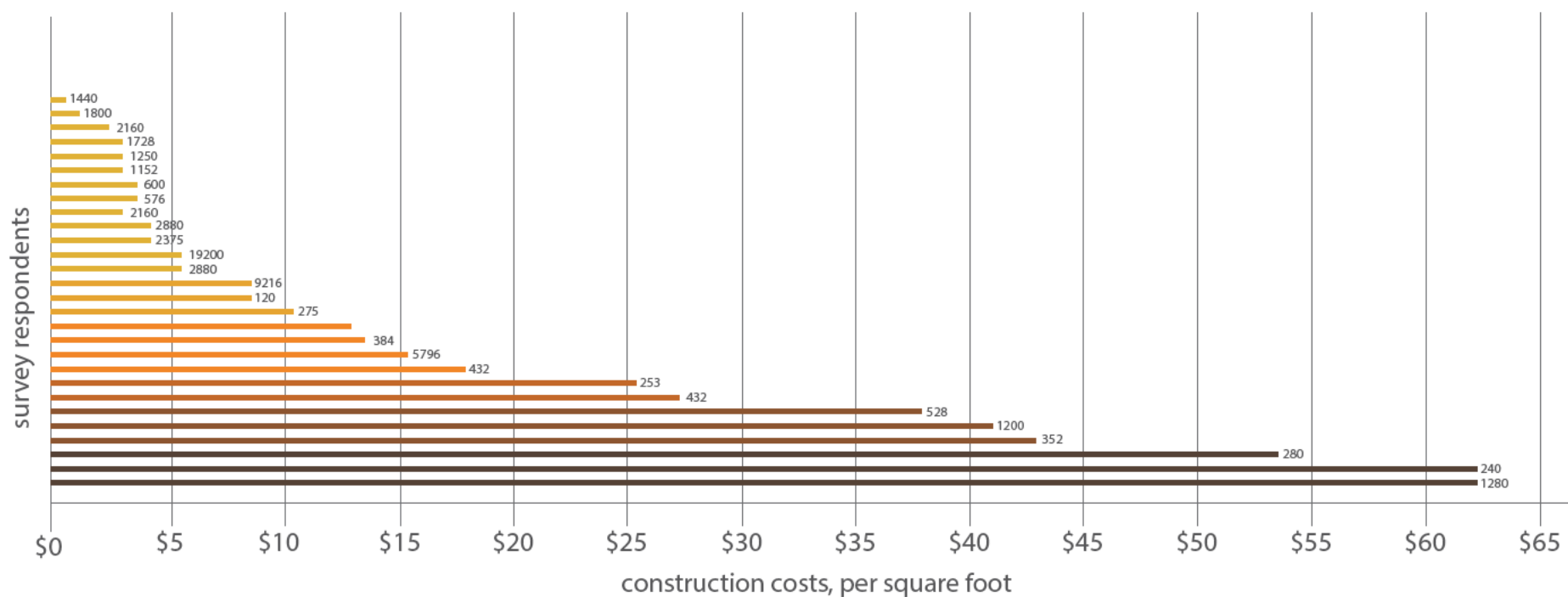


How many people work in your greenhouse throughout the year?

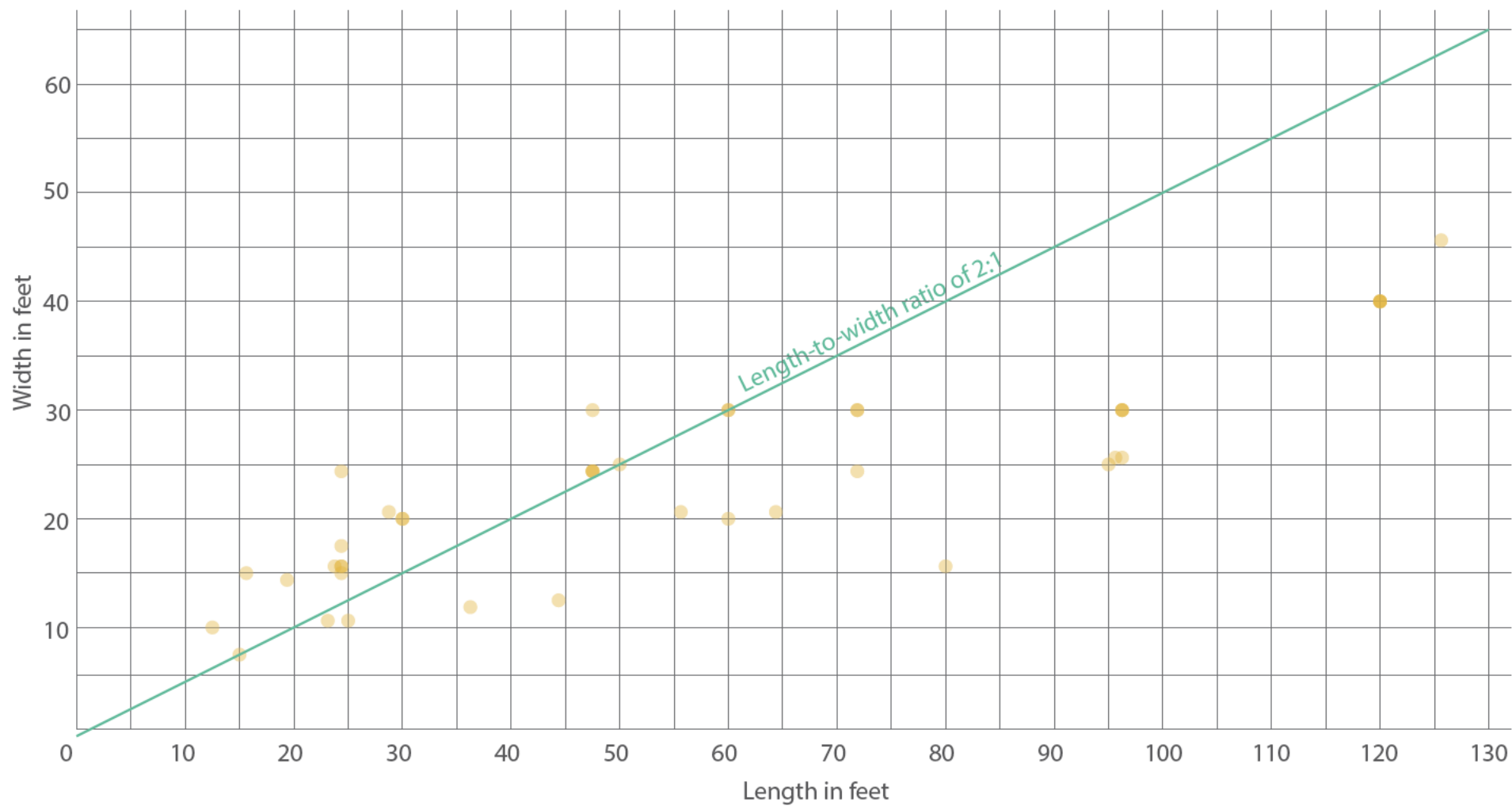


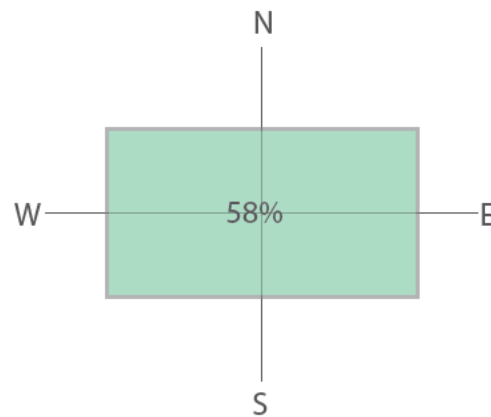
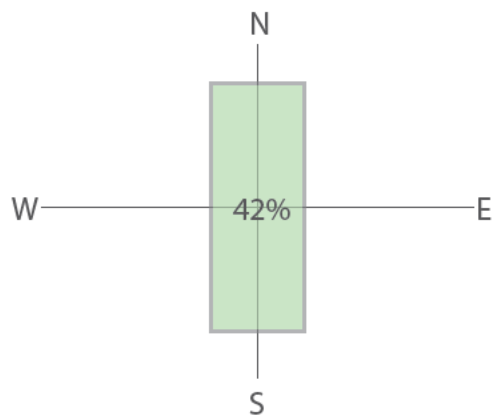
What were the construction costs for your greenhouse(s)?

Each line represents a grower's response to this survey question, with the total square footage noted to the right. With a few exceptions, the smaller greenhouses were reported to have the highest construction costs, per square foot.

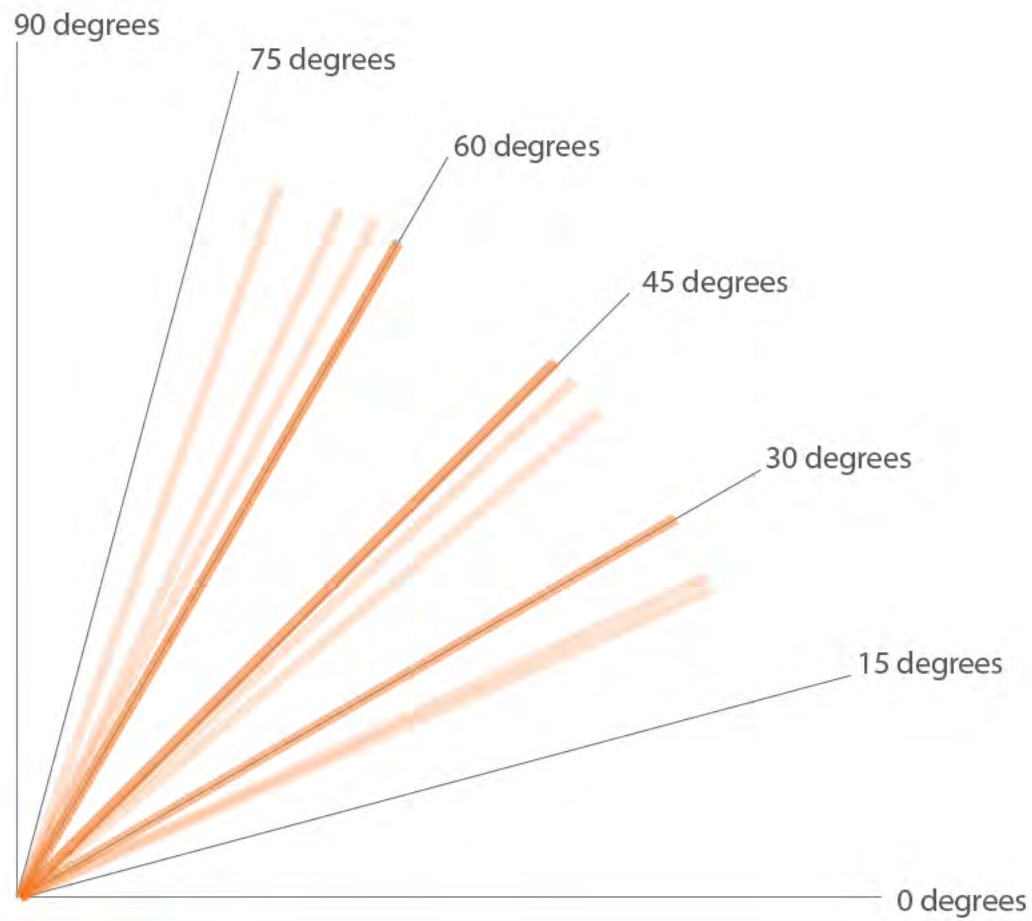


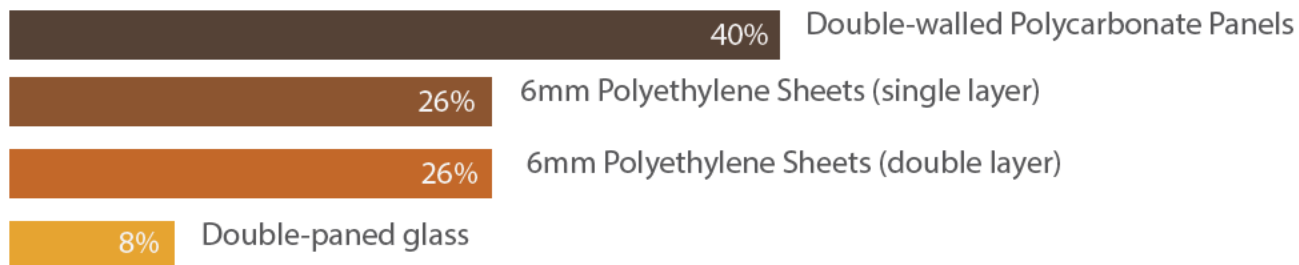
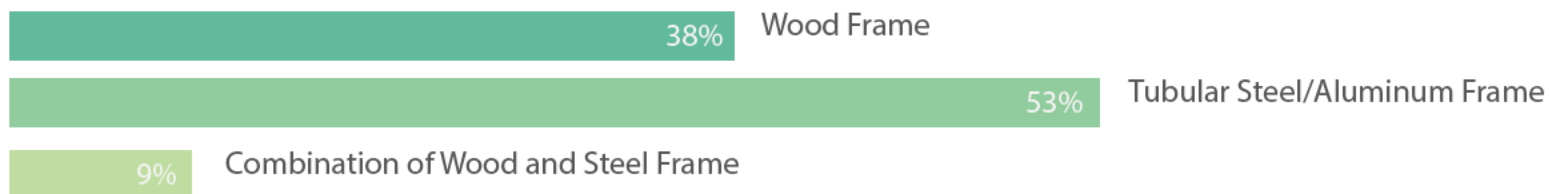
What are the dimensions of your greenhouse?



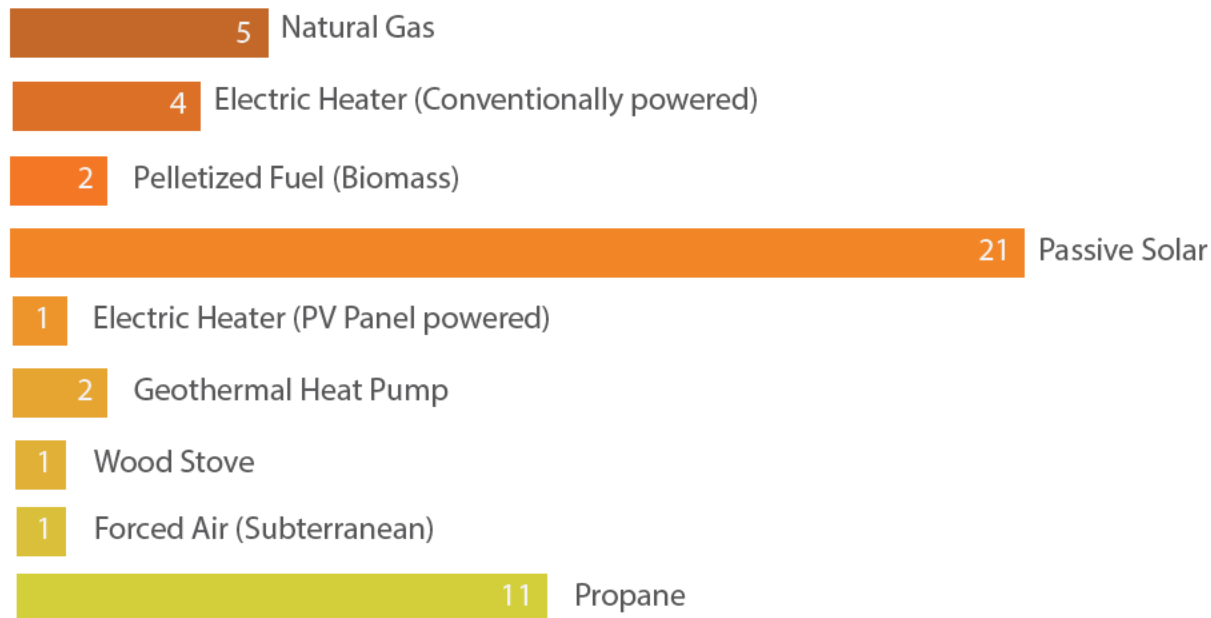
What is the orientation of your greenhouse?**Is your greenhouse attached to another structure, or freestanding?**

At what angle is the glazing material on your greenhouse?

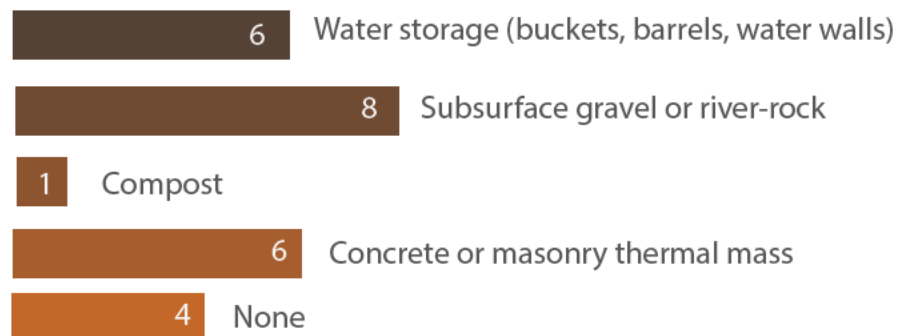


What is the primary glazing material of your greenhouse?**What is the primary structural material that supports the glazing in your greenhouse?**

How is the greenhouse heated? (results measured in number of responses; many growers have multiple heat sources)



Does your greenhouse use any methods to STORE heat? (results measured in number of responses)



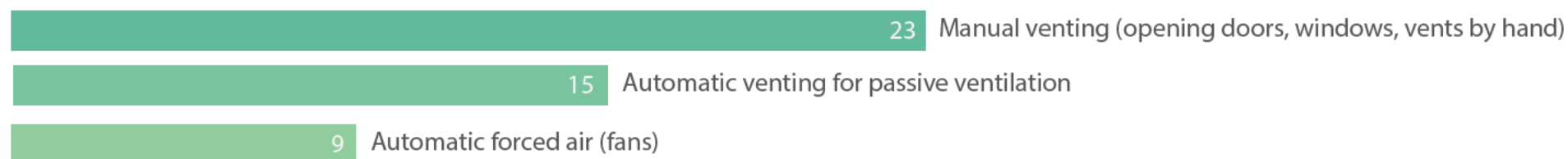
How much non-solar heat energy is consumed during the winter season to maintain the greenhouse?

Survey results were inconclusive. The responses showed that most growers do not have consistent or reliable methods for tracking data related to energy use dedicated to heat sources during the winter.

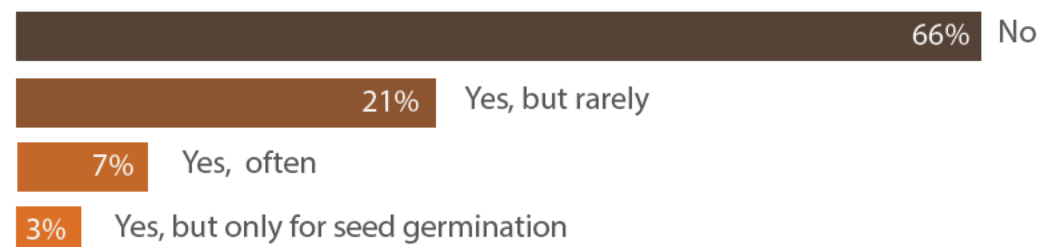
What are your annual heating energy costs in your greenhouse?

Again, survey results were inconclusive in this area. The responses showed that most growers do not have consistent or reliable methods for tracking data related to energy use dedicated to heat sources on an annual basis. As an observation, growers that relied more heavily on passive solar methods generally had a better sense of the amount of money that was spent. Growers that utilize back-up LP systems that are only used during extremely cold nights generally spend between \$50-200 over the course of the year on energy bills.

What is your ventilation strategy to avoid overheating? (results measured in number of responses; many growers use multiple strategies)



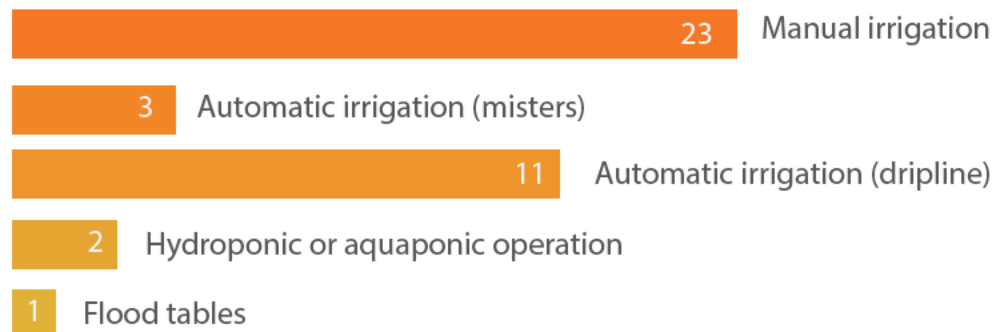
Do you use supplemental lighting in your greenhouse?



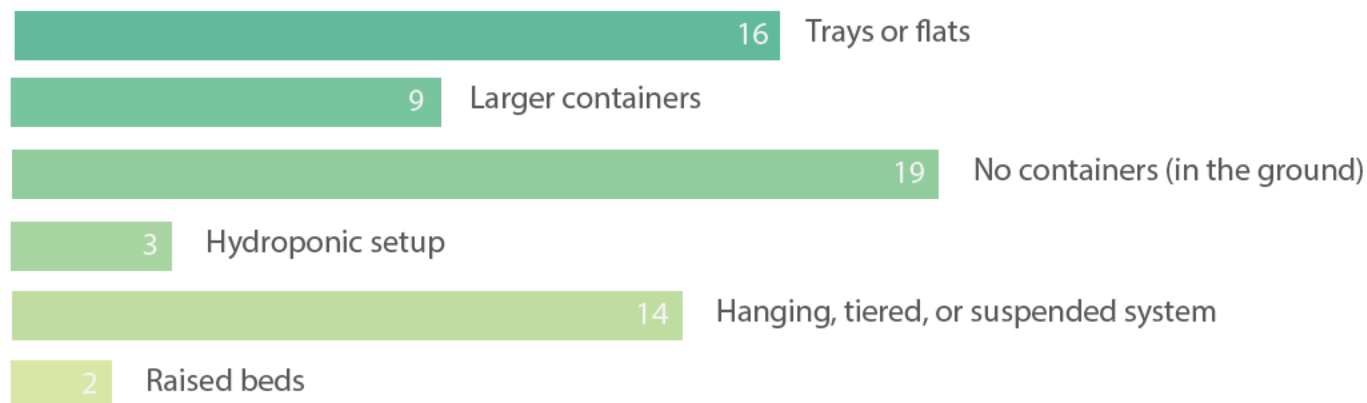
How much do you spend on supplemental lighting electricity in your greenhouse?

Survey results were inconclusive. The responses showed that most growers do not have consistent or reliable methods for tracking data related to energy use dedicated to supplemental lighting electricity.

How are the plants watered? (results are measured in number of responses; many growers use multiple watering methods)



In what type of containers (if any) are the plants grown, in your greenhouse? (results are measured in number of responses)



Have you had any problems or challenges with your greenhouse? (results are measured in number of responses)



Are there any innovative or unique technologies used in your greenhouse?

Heating Systems:

- Many growers are utilizing heat-capture and subterranean heat storage and distribution systems, based on the success of the Garden Goddess model.
- Geothermal heat source
- Compost as a heat source

Monitoring Systems:

- Recording data 3x daily for temperatures at the peak, shoulder, kneewall and under-ground conditions within the greenhouse, as well as ambient air temperatures.
- Using a thermostatic and timer-controlled lighting (and heating) system
- Collecting temperature and humidity data, and using this information to control fans, vents, and irrigation.

Materials:

- Using an insulated cover for the fan/exhaust perforations
- Using all-salvaged materials for construction

Overall Design:

- Constructed a greenhouse with a very high angle of incidence for the glazing
- Cold-frames are integrated into the south-facing kneewall, assisting with ventilation and increasing the area and usable growing space.

Irrigation:

- Greywater collection and an integrated water wall (used for heat storage)

Interior Space Planning:

- Loft system for extra growing room
- Using tomato clips to trellis melons and tomatoes to get more growing area

Do you have any “Lessons Learned” or words of advice to pass along to future cold climate greenhouse builders or operators?

(Selected responses)

“...For a greywater system you need permits and the county has the last word...be nice and know your regulations so you can gently help them learn or become less resistant.”

“You have to be passionate about this. You can’t just go away for the weekend!”

“Experience is the best teacher. Seek out [a] mentor. Read Eliot Coleman.”

“Don’t design for winter heat at the expense of growing-season light. Move heat with liquid rather than air, if possible. Over-do the venting if possible. Carefully consider gravel bed vs. concrete floor: concrete is more expensive, but a gravel bed is difficult to keep clean.”

“Grade the soil at the south end of the greenhouse away from the structure to avoid snow build-up.”

“Develop written operating standards.”

“If you can find someone who is doing the same and share experiences...Also, you need someone who will take over for you so you are not tied to the greenhouse much like “married to the cows.”

“I would highly recommend the NRCS program.”

“Plant beneficial insect attracting plants in the ground or in pots to fight pest infestations. Be sure to have at least 8 hours of direct sunlight when selecting the location.”

“Don’t put off doing it. No one has it 100% figured out for your exact situation, but there’s help and ideas out there. Jump in with both feet and figure it out as you go. The worst thing that could happen is that you have a very nice season extension, and a sunny windproof place to sit in the winter. ”

“...You also need a place to store stuff in your greenhouse, and a place to process the greens. The last thing you want to do is to be carrying a ton of potting soil or other heavy resources back and forth through the cold.”

“Overheating is a real issue, even in the dead of winter. Make sure you have adequate thermal mass and ventilation to deal with overheating. Our big issue in our first and only year of operating, was too hot in the day and too cold in the night.”

“Advice: be prepared for many years of growing pains. What works for one producer may not work for another, but do lots of research and visits before embarking on your own full season greenhouse project. And be prepared to make changes along the way.”

Bibliography

- Aldrich, Robert and John W. Bartok, Jr. Greenhouse Engineering. NRAES-33. Northeast Regional Agricultural Engineering Service, Ithaca: Cornell University, 1984. (Aldrich and Bartok 1984, 1-x)
- Alward, Ron and Andy Shapiro. Low-Cost Passive Solar Greenhouses: A Design and Construction Guide. Butte, Montana: National Center for Appropriate Technology, 1980.
- Bartok, John, Jr. 20~06. "Close down growing space—and save money in winter." GMPPro December 2006. (Bartok 2006)
- Bartok, John Jr. 2006. "Grower 101: Exploring Underbench Heating Options." Greenhouse Product News October, 2006. (Bartok 2006, 54-58)
- Bellows, Barbara. 2008. "Solar Greenhouse Resources." National Sustainable Agriculture Information Service. www.agrisk.umn.edu/cach/ARL01480.htm. (Bellows 2008)
- Benson Agriculture and Food Institute. 2002. "Walipini Construction (The Underground Greenhouse). Brigham Young University 1-29. (Benson Agriculture and Food Institute 2002, 1-29)
- Beshada, E., Q. Zhang and R. Boris. 2006. "Winter performance of a solar energy greenhouse in southern Manitoba." Canadian Biosystems Engineering Vol. 48: 5.1-5.8. (Beshada et al 2006)
- Blomgren, Ted and Tracy Frisch. 2007. "High Tunnels: Using Low-Cost Technology to Increase Yields, Improve Quality and Extend the Season." University of Vermont Center for Sustainable Agriculture. (Blomgren and Frisch 2007, 1-71)
- Both, A.J. 2005. "Creating a Master Plan for Greenhouse Operations." Rutgers Cooperative Research & Extension, (NJAES), Rutgers, The State University of New Jersey. (Both 2005, 1-8)
- Brumfield, Robin, A.J. Both, and George Wulster. 2009. "How Are Greenhouse Growers Coping with Rising Energy Costs." Rutgers, The State University of New Jersey. (Brumfield et al 2009, 1-4)
- Coleman, Eliot. Four-Season Harvest. White River Junction, Vermont: Chelsea Green Publishing Company, 1999. (Coleman 1999)
- Coleman, Eliot. The Winter-Harvest Manual: Farming the Backside of the Calendar. Harborside, ME: Eliot Coleman, 1998. (Coleman 1998)
- Cornell, Tricia. 2012. "Greens in Winter: Cold-Weather Farming in Minnesota." Heavy Table, March 12. heavytable.com/greens-in-winter-cold-weather-farming-in-minnesota/. (Cornell 2012)
- Craft, Mark A. Winter Greens: Solar Greenhouses for Cold Climates. Scarborough, Ontario, Canada: Firefly Books Ltd., 1983.
- Draoui, B., F. Bounaama, T. Boulard, and N. Bibi-Triki. 2013. "In-situ Modelisation of a Greenhouse Climate Including Sensible Heat, Water Vapour and CO2 Balances." EPJ Web of Conferences 45: 1-5. (Draoui et al 2013, 1-5)
- Edey, Anna. Solviva: How to Grow \$500,000 on One Acre, and Peace on Earth. Vineyard Haven, MA: Trailblazer Press, 1998. (Edey 1998, 1-x)
- Erickson, Norm. 2011. "Going Nuts for Clean Energy: Solar-Heated Greenhouse and Biodiesel from Hazelnuts." Clean Energy Resource Teams Case Study: Greenhouse – Southeast Region. www.cleanenergyresourceteams.org. (Erickson 2011)

- Eschbach, Christina. 2011. "Students Take Action and 'Dig-In'—ARTech's Student-Led Greenhouse Project." Clean Energy Resource Teams Case Study: Greenhouse – Southeast Region. www.cleanenergyresourceteams.org. (Eschbach 2011)
- Flanagan, Marie. 2011. "Fresh, Local Winter Produce." Minnesota Monthly, March. <http://www.minnesotamonthly.com/media/Minnesota-Monthly/March-2011/Fresh-Local-Winter-Produce/> (Flanagan 2011)
- Flynn, Dallas. 2009. "Using Solar Energy to Heat the Soil and Extend the Growing Season in High Tunnel Vegetable Production." Greenbook. Minnesota Department of Agriculture, Sustainable Agriculture and IPM Program. (Flynn 2009, 54-57)
- Fontanetta, John and Al Heller. Building and Using a Solar-Heated Geodesic Greenhouse. Charlotte, Vermont: Garden Way Publishing, 1979. (Fontanetta and Heller 1979)
- Ford, Carol and Chuck Waibel. The Northlands Winter Greenhouse Manual. Milan: Garden Goddess Publications, 2009.
- Hayes, John and Dennis Jaehne. Proceedings of the Second Conference on Energy-Conserving, Solar-Heated Greenhouses. Northeast Solar Energy Center and the Solar Energy Research Institute. Plymouth, Massachusetts, 1979. (Hayes and Jaene 1979)
- Lantz, Willie. 2009. "Developing an Energy Efficient, Solar-Heated Greenhouse in Maryland." Ag Innovation Series, Farmer and Ranger Innovations. SARE Project No. ONE09-104. (Lantz 2009, 1-4)
- Latimer, Joyce. 2009. "Dealing with the High Cost of Energy for Greenhouse Operations." Virginia Cooperative Extension Publication 430-101, Virginia Polytechnic Institute and State University. (Latimer, 2009)
- Lewein, Jenna. 2011. "No Winter at Whitewater Gardens Farm: Geothermal Greenhouse Project in Altura, MN." Clean Energy Resource Teams Case Study: Greenhouse – Southeast Region. www.cleanenergyresourceteams.org.
- Lovejoy, Gretchen Mensink. 2013. "New greenhouse at Chatfield allows year-round instruction." The Chatfield News, February 26. (Lovejoy 2013)
- McCullagh, James. The Solar Greenhouse Book. Emmaus, PA: Rodale Press, 1978. (McCullagh 1978, 1-x)
- Miller, Crow and Elizabeth. "Growing winter profits; organic produce from your solar greenhouse." Countryside & Small Stock Journal, Vol. 84 No. 1, January/February 2000. (Miller 2000)
- National Greenhouse Manufacturers Association. 2004. Structural Design Manual. New York: NGMA. (NGMA 2004)
- Panwar, N.L., S.C. Kaushik, and Surendra Kothari. 2011. "Solar greenhouse an option for renewable and sustainable farming." Renewable and Sustainable Energy Reviews, August 2011. (Panwar et al 2011)
- Roberts, W.J, D.R. Mears, J.C. Simpkins, and J.P. Cipolletti. 1981. "Moveable Thermal Insulation for Greenhouses." NJAES Research Paper No. P03130-01-81, New Jersey Agricultural Experiment Station. (Roberts et al 1981, 1-14)

Ross, David S. "Planning and Building a Greenhouse." Adapted from Fact Sheet 645 – University of Maryland Cooperative Extension Service, West Virginia University Extension Service. Accessed June 2013. www.wvu.edu/~agexten/horticult/greenhou/building.htm. (Ross 2013)

Runkle, Eric and A.J. Both. 2011. "Greenhouse Energy Conservation Strategies." Extension Bulletin E-3160. Michigan University Extension. (Runkle and Both 2011, 1-16)

Sayre, Laura. 2005. "Ultimate Season Extension: Winter CSAs use root cellars, hoophouses and on-farm processing to fill members' larders year-round." The New Farm. www.newfarm.rodaleinstitute.org. (Sayre 2005)

Sanford, Scott. 2011. "Greenhouse Unit Heaters: Types, Placement, and Efficiency." (A3907-02) University of Wisconsin-Extension, Cooperative Extension. (Sanford 2011, 1-6)

Schwen, Steven. 1999. "Thermal Banking Greenhouse." SARE Farmer/Ranger Project, Project Number FNC99-256. <http://www.sare.org/Learning-Center/Multimedia/Videos-from-the-Field/Thermal-Banking-Greenhouses> (Schwen 1999)

Seifert, Richard D. 2008. "The Attached Solar Greenhouse." Cooperative Extension Service, University of Alaska, Fairbanks. EEM-01259, 1-4. (Seifert 2008, 1-4)

Smith, Tina and Paul Lopes. 2010. "Greenhouse BMPs: A Handbook for the Greenhouse Industry in Massachusetts." UMass Extension, Massachusetts Department of Agricultural Resources. (Smith and Lopes 2010)

Straten, Gerrit van, Gerard van Willigenburg, Eldert van Henten, Rachel van Ooteghem. Optimal Control of Greenhouse Cultivation. New York: CRC Press, 2011. (Straten et al 2011)

<http://www.sunnyjohn.com/indexpages/shcs.htm>

Benson Agriculture and Food Institute. 2002. "Walipini Construction (The Underground Greenhouse). Brigham Young University 1-29. (Benson Agriculture and Food Institute 2002, 1-29)

Zhang, Dr. Chong and Jordan Langrell. 2007. "Solar Greenhouse Research – 06/07 Results." Profiles in R&D, Manitoba Hydro, July. (Zhang and Langrell 2007)