Growing Garlic in Minnesota

University of Minnesota Extension

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UNIVERSITY OF MINNESOTA EXTENSION

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Introduction

Garlic (*Allium sativum* L.), is a member of the Amaryllidaceae family, which also includes lilies, onions and leeks. It has been cultivated for thousands of years and is widely used for both its culinary and medicinal attributes. As Americans have become more accustomed to garlic flavor and knowledgeable about the many health benefits of eating garlic, the popularity of this crop has increased.

Garlic is native to central Asia. This is a cold climate environment where winter temperatures drop to well below zero. Over hundreds, possibly thousands, of years, garlic has adapted to a wide variety of climates. The varieties that tend to thrive best in Minnesota — those in the three purple stripe families and the porcelain family — tend to be more closely genetically related to the progenitor.

Most garlic in the U.S. is grown commercially in the mild climate of northern California. Varieties adapted to mild climates and then grown in cold climates often do not perform well and can develop a very "hot" flavor. Garlic is an adaptable species, however, and over thousands of years there are also varieties that are adapted to cold climates, often with better and more distinct garlic flavor than the varieties grown in mild climates.

Recent demand for high-quality garlic has prompted an interest in growing garlic for niche markets in the upper Midwest. To help accommodate this market, this publication provides guidelines for growing garlic in cold climates. The major areas addressed include variety descriptions, soil and nutrient requirements, cultural practices, pest management, harvesting, and storage.

Varieties

Over the many years of selection and cultivation, garlic has lost the ability to produce fertile seeds and, in some varieties, flower stalks and flowers are not even formed. Recent research has shown that it is possible to produce true garlic seed, which eventually will improve genetic diversity in the crop. However, garlic from true seed has poor germination rates and is overall difficult to propagate initially. Despite the fact that true garlic seeds cannot be easily produced, there are many different varieties from which to choose. These varieties have been selected over the years, presumably as the result of random mutations.

Garlic varieties are broadly classified into two main categories: **hardneck** and **softneck**.

Hardneck varieties (*Allium sativum* var. *ophioscorodon*) produce a flower stalk, or, technically, a scape, and are often termed "topsetting" or "bolting" varieties (Figure 1). The assumption is that hardneck varieties are most closely related to wild garlic. Flowers, if they are produced, usually abort and form "bulbils" instead. These are small, aerial cloves that have the same genetic make-up as the mother plant (Figure 2). They can be used for propagation, but the bulbs that are formed from bulbils are usually small the first year after planting. Two to four years are required before marketable bulbs are produced from bulbils. Typically, hardneck garlic varieties have 4-12 cloves surrounding the flower stalk. Because of the hard flower stalk, they are difficult to braid and some do not store well.

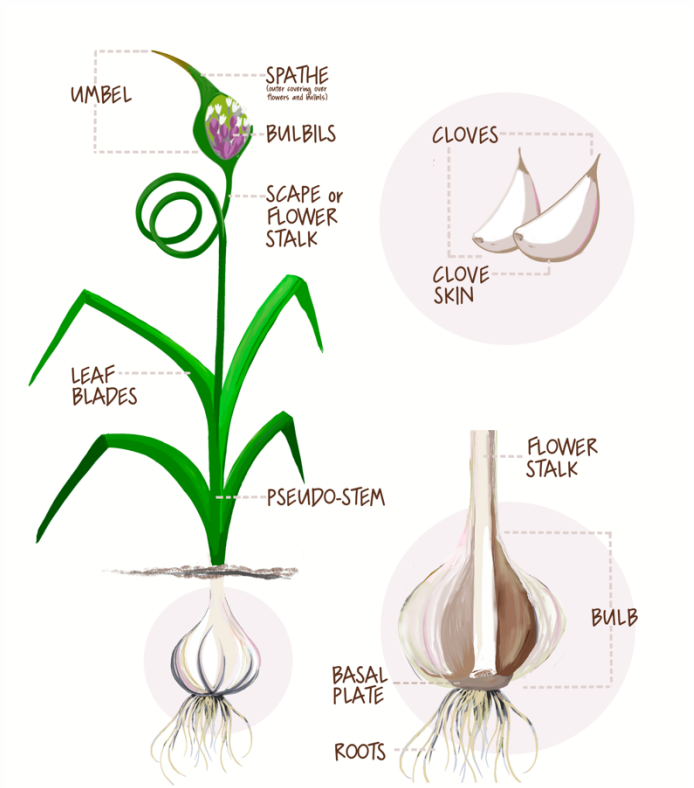

Figure 1. The parts of a hardneck garlic variety, often termed "topsetting" or "bolting".

Figure 2. Small, aerial cloves that have the same genetic make-up as the mother plant are known as bulbils.

Softneck varieties (*Allium sativum* var. *sativum*) do not produce a flower stalk. These are the types of garlic that are commonly used in California for commercial mass production; although more recently some hardneck varieties are being grown on a large scale in various parts of the world and imported to the U.S. as well. There are some softneck varieties that are suitable for cold climates. Softneck varieties are considered to be the most domesticated varieties due to minimal flower stalk and bulbil production. Each bulb generally contains between 10-40 cloves arranged in multiple layers somewhat like an artichoke. Softneck garlic generally has a longer shelf life than hardneck garlic and typically can be stored for 6-8 months without significant deterioration. They also are easy to braid.

Based on genetic DNA analysis there are 10 major garlic types; however, Varietal characteristics can vary tremendously from one location to another, complicating variety selection. Climate can have a significant impact on garlic flower stalk formation as well as garlic taste. For example, a variety may be considered a softneck in one location, but in other locations it may produce a flower stalk. Occasionally, only a partial flower stalk is produced and bulbils will form directly above the bulb. Since there is no standardization, some garlic seed producers will rename particular varieties, leading to more confusion. It is best to try out several different varieties for a few years and select those that do best in your area. Characteristics of the 10 major garlic types when grown in colder climates are described below. Seed garlic may be purchased from various vendors listed on the Sustainable Farming Association garlic webpage, the Minnesota Grown Directory, or from vendors selling garlic online, at Minnesota Garlic Festival, and at regional farmers markets.

Varietal descriptions

Rocambole

Moderately sized plant (3-4 feet tall with scape uncurled), characterized by a scape that coils 2-3 times before straightening out. Bulbils are numerous and generally a purple color. Bulbs are off-white with purple streaks. Clove skins are brownish and easy to peel. Bulbs store for about 4-5 months. Generally performs well in cold climates. Prone to double cloves (Figure 3).

Figure 3. Rocambole garlic plants are prone to double cloves.

- Typical named selections include: German Red, German Brown, Spanish Roja, Russian Red, Killarney Red, Montana Giant

Purple Stripe

Moderately sized plant (3-5 feet tall with scape uncurled), characterized by a scape with ¾ of a coil and others just form a downwards U before straightening out. Bulbils are numerous and generally a purple color. Bulbs have purple streaks. Clove skins are brownish and more difficult to peel than rocamboles. Bulbs store for about 5-7 months. Generally performs well in cold climates. A typical bulb has 8-12 cloves and one pound of garlic will supply about 60 cloves. Double cloves rarely occur.

- Typical named selections include: Chesnok Red, Persian Star, Dugunsky, Deerfield Purple

Glazed Purple Stripe

Similar to Purple Stripe except wrapper skins are usually more glossy in appearance and clove color is more intensely purple with fewer cloves per bulb. Environmental conditions can affect the appearance and in some cases it is difficult to distinguish a Glazed Purple Stripe for a Purple Stripe. One pound of garlic will supply about 60 cloves. Scape tends to form a full coil before straightening out.

- Typical named selections include: Purple Glazer, Red Rezan

Marbled Purple Stripe

Bulbs actually look more similar to Rocamboles than Purple Stripes, but genetic analysis places them closer to Purple Stripes. Scapes tend to be weak in some strains and form somewhat random coils. A typical bulb has 4-7 cloves and one pound of garlic will supply about 50 cloves. Plants are very vigorous in cold climates.

- Typical named selections include: Siberian, Brown Tempest, Metachi, Estonia, Krasnodar Red

Porcelain

Large and vigorous plants (4-6 feet tall with scape uncurled). They are characterized by a scape with loose and somewhat random coils before straightening out. Bulbils are numerous, small, and

generally a white color. Bulbs are large and typically contain 4-6 cloves. This characteristic is great for cooks, but growers need to save more of their crop for seed. Clove skins are smooth and white. They tend to be more difficult to peel than Rocamboles. Double cloves are rare. Bulbs store for about 5-7 months. Generally performs well in cold climates. One pound of garlic will supply about 35 cloves.

- Typical named selections include: Armenian, Georgian Crystal, Music, Polish Hardneck, Zemo, Georgian Fire, Northern White, German White, Krasnodar White

Artichoke

This garlic type is usually a softneck but may partially bolt following cold winters (Figure 4). In some cases the bulbils form just above the bulb making the bulb unmarketable. In a mild winter only 1-2% will bolt. In a cold winter without snow cover, 70-100% may bolt. Bulbils that do appear are usually purple. Bulb color is whitish to purple blush. Bulbs typically contain 15-30 cloves and one pound of bulbs will supply about 80 cloves. This is usually the most productive softneck type in cold climates. Cloves are difficult to peel. Bulbs store for 6-9 months.

Figure 4. Artichoke garlic plants are usually a softneck type, but may partially bolt following a cold winter.

- Typical named selections include: Lorz Italian, Inchellium Red, California Early, Susanville, California Late, Early Red Italian, Machashi, Red Toch, New York White

Asiatic

A shorter garlic plant that is about 3 feet tall when the scape is mature. Originally thought to be closely related to artichoke varieties, but further genetic analysis suggests it is a hardneck type. A flower stalk almost always forms under Minnesota conditions. Scapes generally do not curl and may be somewhat drooping with a long characteristic bulbil capsule. Bulbils are much larger than those produced on other garlic types and are usually dark purple or white in the case of Sakura/Japanese. There are usually four to eight large cloves per bulb and one pound of bulbs will provide about 50 cloves. Double cloves do occur in this type. Cloves are brownish and bulb color varies from white to pink to purple striped. Clove skins are somewhat tight making it difficult to peel. Generally they perform well in cold climates. In some selections, cloves are very prone to splitting through the bulb skins if harvested too late. Bulbs typically can be stored for 5-7 months.

- Typical named selections include: Asian Tempest, Japanese, Wonha, Sakura, Pyong Vang

Turban

Genetically related to softneck types, but often forms a flower stalk under Minnesota conditions. Scapes are weak and tend to form a downwards U. The purple bulbils are numerous and small. There are usually 7-11 cloves per bulb and one pound of bulbs will supply about 60 cloves. Double cloves are not common in this type. Cloves are brownish and bulb color is usually dark purple striped. Clove skins are loose making it easy to peel. This type does not store well and typically only lasts 3-5 months. The advantage of this type is that it matures 1-3 weeks earlier than most other garlic types and therefore can be used for the early market.

- Typical named selections include: Red Janice, Blossom, Xian, Tzan, Chinese Stripe

Creole

Genetically related to softneck types, but often forms a flower stalk under Minnesota conditions. Scapes that do form are weak and curl randomly, sometimes just forming a downward U. Bulbils are small and usually white to pink. There are usually 8-15 cloves per bulb and one pound of bulbs will supply about 80 cloves. Creole garlic is most suited for warm climates and mild winters. For this reason, bulb size is small (usually less than two inches) under Minnesota conditions, especially after a cold open winter. However, the deeply dark purple-red clove skins and generally sweeter taste make this garlic type unique and desirable (Figure 5). Bulb size can sometimes be improved by planting early in the spring as soon as the ground thaws. Clove skins are somewhat tight making peeling difficult. Bulbs typically can be stored for 6-8 months.

Figure 5. Creole garlic's deeply dark purple-red clove skins and generally sweeter taste make this garlic type unique and desirable.

- Typical named selections include: Ajo Rojo, Burgundy, Creole Red

Silverskin

A true softneck type even under Minnesota conditions most years. The lack of a flower stalk makes this garlic type the best for braiding. Occasionally flower stalks will form following a cold winter. Clove number per bulb ranges from 18-40 and one pound of bulbs will supply about 90 cloves. Silverskin garlic is most suited for warm climates and mild winters. For this reason, bulb size is small (usually less than 2 inches) under Minnesota conditions, especially after a cold, open winter.

Figure 6. Silverskin garlic plants will "lay down" about one week before harvest due to their weak necks.

Bulb size can be larger than 2 inches following a mild winter. Because of their weak necks, the plants will lay down (lodge) about one week before harvest (Figure 6). Bulb size can sometimes be improved by planting early in the spring as soon as the ground thaws. Clove skins are somewhat tight making peeling difficult. Bulbs typically can be stored for up to one year.

- Typical named selections include: Silver White, Nookota Rose, Mild French, S&H Silver, Idaho Silver

Note: Elephant garlic is not a true garlic, but is actually a type of leek, *Allium ampeloprasum*. It can grow much larger than true garlic with each bulb of five to six cloves weighing as much as one pound. The taste of elephant garlic is much milder than true garlic, and in cold climates can develop a sharp or bitter taste.

Soils

Site selection and organic matter

Garlic grows best on well-drained soils high in organic matter. Sandy loam or loam soils have the most ideal texture for garlic. Drought or excessively wet conditions (i.e. low spots) will reduce yields and marketable bulbs. Planting site should be located in an area with well drained soils. Garlic can be planted on gentle slopes along the contour. Raised beds can be used to facilitate good drainage as well particularly on clay or heavy soils.

Use of a green manure crop such as buckwheat, oats, and field peas or other legumes tilled in a few weeks before planting is recommended to improve soil physical properties. There are many options for cover crops, for further information see: https://extension.umn.edu/cover-crops/planting-cover-crops. Well-composted manure applied and incorporated at a rate of 20-30 tons/acre (1000-1500 lb per 1000 sq. ft.) has also been shown to be ideal as a soil amendment, especially on low organic matter soils. Care should be taken not to over-apply compost as phosphorus in particular can build up to excessive levels.

pH requirements

The optimum soil pH for garlic is between 6 and 7, though a wider range can be tolerated, between 5.5-7.8 pH. Liming is recommended if the pH is less than 5.8. Rates to apply and incorporate should be based on soil test recommendations. There are resources available through Extension to adjust soil pH.

Fertilizer requirements

Nitrogen

Garlic has a moderate to high demand for nitrogen. Recommendations for nitrogen are based on previous crop and organic matter content (Table 1). Reduce recommended rates of nitrogen by: 70 lb N/acre if the previous crop is alfalfa, 40 lb N/acre if the previous crop is clover, and 20 lb N/acre if the previous crop is soybean or peas.

For quick release nitrogen sources like urea, ammonium sulfate, chilean nitrate, or blood meal, about one-third to one-half of the recommended N should be broadcast and incorporated in the fall before planting. The remainder of the N should be top-dressed and watered in one to two weeks after emergence in the spring. Bulbing may be delayed if high rates of nitrogen are applied

late in the spring. For slow release sources like manure, composted manure or polymer-coated urea, most of the nitrogen can be applied in the fall before planting. If manure or compost has been applied, be sure to take credit for the nutrient value of these amendments. Obtaining a nutrient analysis of these organic amendments before application is strongly recommended. Additional N may not be needed in the spring if adequate amounts of compost or other slow release sources have been applied in the fall. Benefits of spring nitrogen application depend on the type of soil. Sandy low organic matter soils will benefit from a spring application more than clayey high organic matter soils.

Symptoms of nitrogen deficiency include a yellowing of older leaves and leaf tips, general yellowing of the plant, poor vigor, and low yields. Comparison of nitrogen deficient and nitrogen sufficient plants is shown in Figures 7 and 8. See note below about yellow tips.

Figure 7. Garlic plants with sufficient nitrogen.

Figure 8. Garlic plants with insufficient nitrogen. Note yellowing.

Table 1. Nitrogen recommendations for garlic.

Soil Organic Matter Level (% O.M.)	Nitrogen to apply (lb/acre)
Low (<3.1%)	120
Medium (3.1-4.5%)	100
High (4.6-19%)	80
Organic soil (>19%)	50

Phosphorus and potassium

Soil tests should be taken before planting to determine phosphorus and potassium needs. Recommendations for phosphorus based on a soil test are provided in Table 2. Use the Bray P1 test if soil pH is 7.4 or less and use the Olsen test if soil pH is greater than 7.4. Recommendations for potassium based on a soil test are provided in Table 3. All P and K fertilizers should be incorporated before planting. Symptoms of P deficiency include dark green to purple leaves and stunted growth. Symptoms of K deficiency include marginal scorching of the older leaves.

Table 2. Phosphate fertilizer guidelines for garlic based on either the Bray-P1 or Olsen soil methods test.

Bray-P1 (soil pH is 7.4 or less)	0-10 ppm	11-20 ppm	21-30 ppm	31-40 ppm	41-50 ppm	51+ ppm
Olsen (soil pH is 7.5 or more)	0-7 ppm	8-15 ppm	16-25 ppm	26-33 ppm	34-41 ppm	42+ ppm
Suggested lb of P_2O_5 per acre	200	150	100	75	50	0

Table 3. Potassium recommendations for garlic based on soil test.

Soil test K level	0-40 ppm	41-80 ppm	81-120 ppm	121-160 ppm	161-200 ppm	200+ ppm
Suggested lb of K_2O per acre	200	150	100	75	50	0

Calcium, Magnesium, and Sulfur

Calcium and magnesium may be low in acid soils. The need for these elements usually can be met by following lime recommendations. Sulfur is a major constituent of compounds believed to be involved with the medicinal qualities of garlic. Yield responses to sulfur additions are not common in garlic, but sulfur fertilizers may affect garlic flavor and medicinal compounds.

Micronutrients

Garlic response to micronutrients has not been reported in Minnesota. Addition of compost or other types of organic amendments will help to ensure that micronutrient supplies are adequate.

Tissue analysis

Use tissue analysis to help diagnose any suspected nutrient deficiencies and fine-tune a fertilizer program. Sufficiency ranges of the most recently matured leaf sampled at initial bulbing from high yielding garlic plants are presented in Table 4. Tissue samples can be sent in for analysis to the UMN Soil Testing Lab.

Table 4. Nutrient sufficiency ranges in the most recently matured leaf of garlic sampled at initial bulbing.

N	P	K	Ca	Mg	S	Mn	Fe	Zn	Cu	B	Mo
%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm
3.0-4.5	0.3-0.6	3.0-4.5	1.0-1.8	0.25-0.4	0.3-0.7	30-60	50-70	13-20	3-5	20-30	0.5-2

Many garlic varieties are susceptible to yellow tips. This disorder can occur even in the presence of adequate fertility. Unless the yellow tips occur early in the season (before bulbing) or the yellowing covers more than one third of the leaf, the disorder does not appear to have a drastic effect on yield. Yellow tips early in the season are usually a sign of water, cold or nutrient stress or disease (see below).

Planting

Prior to planting, soils should be tilled to provide a loose growing bed for optimal bulb growth. Since true seeds are not easily produced by the garlic plant, cloves of the bulb are used for clonal propagation. First time garlic growers should purchase bulbs for seed cloves from reputable regional garlic growers who test for major diseases of concern. Established growers usually save about 15-25 percent of their crop, depending on variety, for planting the subsequent year.

Porcelain varieties require a higher percentage of the crop saved for seed than all other varieties. Depending on quantity ordered and variety, the price of garlic seed cloves can range from $12-30 per pound. Planting cloves from garlic purchased at the grocery store is not recommended; this garlic is mainly adapted to milder climates and is usually treated or stored at temperatures not conducive for proper bulb formation.

Time of planting is critical since both optimum shoot and bulb development require a cold treatment (vernalization). However, field trials have shown that the planting window is much greater than previously thought. Garlic in Minnesota should be planted in the fall, usually within one to two weeks after the first killing frost (32˚ F). In northern Minnesota, planting during the third to fourth week of September is recommended, while in southern Minnesota planting around the first or second week of October is recommended. Ideally, roots should be developing and shoots should be emerging from the clove but not above the soil at the time of the first hard freeze (28˚ F). However, field trials have shown that the planting window can be wider than those two-week periods. Planting windows across Minnesota can last from mid-September until the ground freezes. There are risks to planting too early or two late that may outweigh the advantages. Freeze damage to top growth before winter is wasted energy. Planting too late will be difficult due to frozen soils. Planting can be done in phases to reduce risks of planting too early or late. Garlic shoots will emerge from the ground in late March or early April. Earlier emergence and growth in the spring can be accomplished by planting cloves stored in the refrigerator for three to four weeks prior to planting. This practice can also result in increased bulb size at harvest.

Spring planting is not recommended unless the cloves can be given a proper cold treatment like a few weeks in a refrigerator prior to planting. The home freezer is not a proper cold treatment and will kill the cloves. Garlic planted in the spring without a cold treatment will often produce weak shoots and poorly-developed bulbs. Lack of scape development in hardneck garlic and bulbing in all garlic is usually due to an inadequate cold treatment.

Spacing depends on a number of factors and there are many spacing arrangements that will yield a productive crop. Close spacing results in higher yield on an area basis but smaller bulbs, while spacing farther apart will result in lower total yields but larger bulbs. A common practice is 6-8 inch spacing between bulbs, and there is a lot of variation in between row spacing recommendations, which range from 12-40 inches. The best row spacing will depend on the cultivation method. Growers who use mechanical cultivation methods will need wider row spacing, but for those who cultivate by hand, narrower row spacing will leave less room for weeds.

One example of successful spacing is to plant cloves in two foot beds with four rows and 8" spacing within and between rows and a 2' walkway between beds (Figures 9 and 10). Other options include single rows spaced 30" inches apart and cloves spaced 6" apart within the row. This wide spacing between rows allows for mechanical cultivation for weed control. Typically, yields of garlic planted in double rows 30 inches apart will range from 3-5 tons per acre (138-230 lb/1000 sq. ft).

Higher yields can be attained with closer spacing. The amount of garlic to purchase will depend on the area to be planted, spacing, and variety. Some varieties have more plantable cloves per bulb than others. Generally, there are about 30-50 cloves per pound of garlic bulbs. Therefore, garlic spaced at 6" within a row 100' in length will require approximately 4 pounds of cloves or 4-5 pounds of bulbs. Generally, seed cloves from one pound of garlic bulbs will yield between 4-8 pounds of harvestable bulbs. This will also vary, of course, with growing conditions and variety.

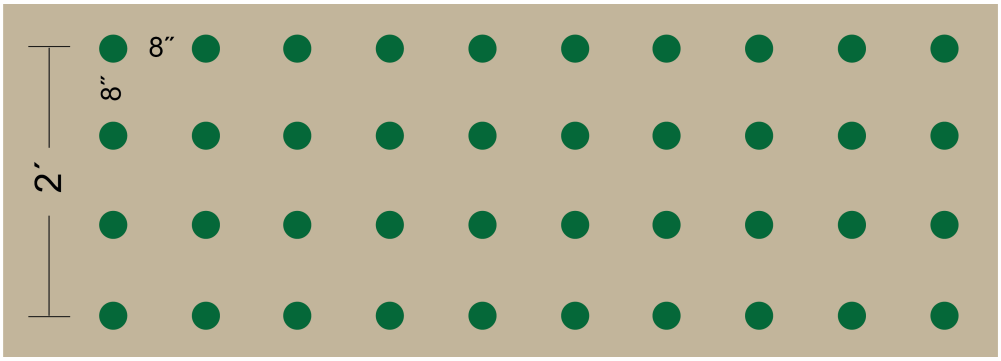

Figure 9. An example of garlic spacing in beds. Allow for a 2' walkway between beds. A 50' bed would require 300 seedcloves.

Individual cloves should be separated from the bulb the day of or up to one week before planting. Cloves separated for longer than that may dry out. Generally, larger cloves from larger bulbs will produce the largest bulbs. In some varieties, large cloves may be actually two cloves fused together, known as a "double". These doubles will produce two bulbs that become flattened as they grow together (Figure 3).

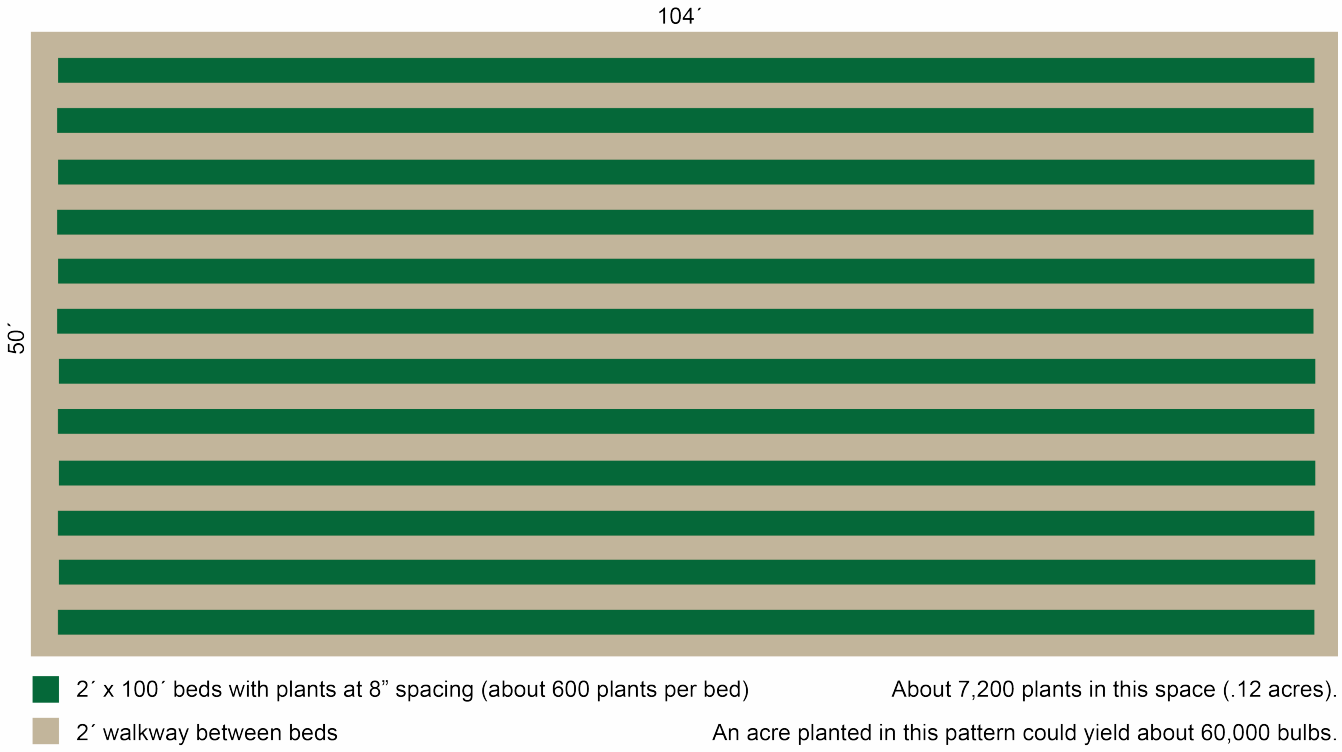

Figure 10. An example of a planting configuration for garlic.

The result is less marketable, poorly shaped bulbs. Double cloves are more prevalent in certain hardneck varieties, such as German Red and other Rocambole types, compared to Porcelain and softneck varieties.

Cloves should be planted with the pointed side up. Cloves planted upside down will develop a curved shoot that results in misshapen bulbs (Figure 11). The base of the clove should be planted two to three inches below the soil surface. As garlic grows, tractile roots pull cloves deeper into the ground. For small acreage, cloves are generally planted by hand. Large commercial growers use a mechanical planter.

Figure 11. Cloves planted upside down will develop a curved shoot.

Mulching

Use of mulch is recommended for several reasons: to protect garlic from frost damage, to help control weeds, moderate fluctuations in soil temperature in winter and early spring, and to preserve moisture in the soil. Garlic roots and shoots tolerate freezing conditions provided that sudden drops in temperature do not occur. Mulch can be applied any time after planting.
In general, mulching within five weeks after planting is suggested. Rows should be covered with a 3-4" layer of seed-free straw. If straw is not available, chopped corn stalks, soybean straw, or fall tree leaves can also be used as mulch.

Garlic shoots can tolerate air temperatures as low as 20˚ F without damage. Plant death, multiple shoots, and poor bulb development may occur if bulbs and shoots are exposed to temperatures below 10˚ F (Figures 12 and 13). In general, mulch should only be removed in spring if plants are having trouble pushing through it, which can occur for some softneck varieties. Mulch removal is not necessary for most hardneck varieties and weed control will be much easier if mulch is left on. There may be a few instances when some growers in the more northern latitudes of the state will remove the mulch completely in the spring to allow the soil to warm faster, then return the mulch

Figure 12. Garlic shoots damaged by cold weather.

Figure 13. Garlic plant damaged by cold weather.

after the shoots are about 6" tall. However, this practice is labor intensive and not recommended in most situations.

Plastic mulch may be a good option on farms that already use it for other crops. Caution is advised when using drip tape under plastic mulch because excessive moisture can lead to fusarium problems. Use of plastic is regulated for organic production, so check with your certifier before using.

Irrigation

Garlic has a relatively shallow root system and is sensitive to dry soil conditions. The amount of water to apply will depend on soil type. Irrigation is essential on sandy soils and may be beneficial in some years on finer-textured soils depending on rainfall amounts. Enough irrigation should be provided so that the available water holding capacity does not drop below about 50 percent.

The most critical stage for irrigation is during bulbing (end of May to early July). Lack of irrigation or rainfall during this stage will result in smaller bulbs and earlier maturity. Irrigation should be stopped about two weeks before harvest to avoid stained bulb wrappers and diseases. Standing water can be the worst enemy of garlic, so care should be taken not to overwater.

A soil's available water holding capacity (AWHC) can be obtained from the local Soil and Water Conservation District office or county soil survey. Table 5 shows AWHC estimations for some typical soil textures in Minnesota. Find out more about soil surveys at https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Table 5. Available water holding capacities for several Minnesota soils.

Soil texture	Available water holding capacity	
	Inches per inch of soil	Inches per foot of soil
Loamy fine sand	0.08-0.12	0.96-1.44
Sandy loam	0.10-0.18	1.20-2.16
Loam	0.14-0.22	1.68-2.64
Silt loam	0.18-0.23	2.16-2.76
Clay loam	0.16-0.18	1.92-2.16

Soil Water Monitoring

Two common ways of estimating soil water deficit to help schedule irrigation are: 1) using soil moisture sensors and, (2) estimating soil moisture using the feel and appearance method with a soil probe. Soil moisture sensors are divided into two categories depending on the technology they use: 1) Sensors that measure volumetric water content and 2) Sensors that measure soil tension when placed in the soil profile.

Volumetric water content is the volume of water per volume of soil. It is usually expressed as a percentage. For example, 25% volumetric water content (VWC) means 0.25 cubic inch of water per cubic inch of soil. When compared with the maximum amount of water that the soil can hold (AWHC) or field capacity, volumetric water content (VWC) measurements can be used to measure soil water deficit for irrigation scheduling:

Soil water depletion/deficit (inches) = soil water content at field capacity (inches) – current soil water content (inches)

A better understanding of the basic principles, definitions, and terms behind the soil-water-plant relationship is essential to effectively utilize soil moisture sensors. For more information, visit: https://extension.umn.edu/irrigation/basics-irrigation-scheduling.

Soil water tension can be monitored at a given point in the active root zone by electrical resistant moisture blocks or tensiometers. Soil tension or suction is a measurement usually expressed in centibars, and describes how tightly water is held to the soil particles.

If the soil texture is known, the amount of soil water deficit for a given tension reading can be estimated by referring to tables in the following website: https://extension.umn.edu/irrigation/soil-moisture-sensors-irrigation-scheduling

Tensiometers directly read soil tension between 0 and 80 centibars, and work best in sandy loam or lighter textured soils. Resistance blocks, although slightly less accurate than tensiometers, work in a wider range of soil textures. Some types are as accurate in coarse textured soils as tensiometers.

To obtain representative soil moisture readings with any sensor type, it should be installed and left throughout the irrigation season, preferably at two or more locations in the field. If using portable sensors, access tubes should be installed and left throughout the irrigation season.Two depths are generally desired at each location. These depths should be about one-third and two-thirds of the active root zone, or at around six-inch and 12-inch depths.

The feel/appearance method involves collecting soil samples in the root zone with a probe or a spade. The soil water depletion of each sample can be estimated by feeling the soil and comparing its appearance to data in the NRCS bulletin. Soil samples should be taken from the top six inches to 12 inches in the root zone and at several locations in the field. Sum up the estimations from various depths for one location to estimate the total soil water depletion in the root zone. This method requires frequent use for an operator to develop the art of estimating soil water consistently.

For more information on in-field soil moisture monitoring tools refer to these two websites:

https://extension.umn.edu/irrigation/estimating-soil-moisture-feel-and-appearance-method

https://nrcspad.sc.egov.usda.gov/distributioncenter/product.aspx?ProductID=199.

Removal of scapes

For hardneck garlic, scapes should be removed to encourage greater bulb growth. Research in Minnesota has shown that yields can be reduced by 20 percent to 30 percent if the scape is allowed to mature. Yields are most affected in poorly fertilized soil, and only minimally (< 5%) affected in high organic matter, well-fertilized soil. The time to remove the scape is just after the initiation of curling but may be removed any time after emergence (Figures 14 and 15). Scapes should be clipped right above the top leaf without damaging leaves. In some varieties and under wet conditions, the scape might rot after removal causing structural damage and risk of infection if water fills in.

Figure 14. Remove garlic scapes just after the initiation of curling.

Figure 15. Scapes should be clipped right above the top leaf without damaging leaves.

Figure 16. Immature scapes are edible and can be collected for sale.

The immature scapes are edible. They can be sold at farmers markets as a green and used in stir fries, salads, or steamed vegetables, and there is a growing market for processed scape products like pesto and pickled scapes. Therefore, after removal, they can be sold as there is a secondary market for them (Figure 16). In some situations, scapes can be left on if a market for the bulbils is available to offset the loss in bulb yield. More mature scapes are sometimes used in flower arrangements.

Weed control

Garlic is a poor competitor with weeds. Unless weeds are controlled early, they can easily overtake young garlic plants, causing significant yield losses. Hand weeding and mechanical control are the most common weed control methods for MN growers. Before garlic is planted, use of a green manure, or cover crop, such as buckwheat plowed down before going to seed, will reduce annual weed competition. If perennial weeds are a problem, for conventional (nonorganic) garlic production, application of a broad spectrum, systemic herbicide such as glyphosate is recommended in late August or early September, before planting garlic in the fall. Tillage can reduce weed pressure, especially if done more than once before bed preparation. Be sure to use straw free of seed as mulch. If desired, a few soil-applied and post-emergence herbicides are registered for use on garlic. Always read and follow herbicide label instructions for use. For information on general management for garlic production and registered herbicides for use on garlic, see the Midwest Vegetable Production Guide: https://mdc.itap.purdue.edu/item.asp?Item_Number=ID-56.

Pests and diseases

Pests

Garlic Bloat Nematode (GBN) (*Ditylenchus dipsaci)*

WHAT IT IS Parasitic nematode (Figure 17)

SYMPTOMS Stunting, twisted, and pale leaves, usually followed by rotting of the lower stem and base of the bulb. In severely infested fields, young plants become enlarged and deformed and frequently die (Figure 18). Symptoms can be subtle in early stages.

HOW TO IDENTIFY Laboratory test to confirm (https://www.sfa-mn.org/garlic-bloat-nematode-testing/).

Figure 17. Garlic bloat nematode.

Figure 18. Garlic infected with garlic bloat nematode.

CONTROL MEASURES GBN is usually introduced in infected seed and can be devastating if left uncontrolled. Do not use or sell garlic for seed if the garlic has tested positive for GBN. Keeping a careful record of where seed is obtained and planted in which field can be helpful if GBN is detected later. Control measures include planting clean seed stock, elimination of volunteer garlic and onions, and proper rotation. The nematodes are primarily located in infected tissue, so to control this pest, infected plants should be removed by digging and then burned. Do not plant garlic following garlic or any member of the onion family, or alternate hosts such as pea, parsley, celery, and salsify for a minimum of four years.

PREVALENCE IN MINNESOTA GBN is present in the Upper Midwest and has been devastating to some farms that focus on seed production. However, proactive and diligent testing and education programs have slowed the spread of this pathogen.

Diseases

Aster Yellows (AYP)

WHAT IT IS A virus-like bacterial infection (phytoplasma) transmitted by leafhoppers (*Macrosteles quadrilineatus*).

SYMPTOMS At early stages of infection there may be no symptoms, but plants will later show:

- Premature yellowing and dieback of garlic plants, usually starting on the new growth first (Figure 19)
- Small, often soft bulbs

- Dark streaking or discoloration of wrapper (Figure 20 and 21)
- Blasting of flowers if scapes are left on (Figure 22)
- Unusual smell to bulb
- Very poor emergence of infected seed; plants that do emerge often eventually die.

Figure 19. Premature yellowing and dieback of garlic plants due to aster yellows.

Figure 20. Aster yellows causes dark streaking or discoloration of wrapper.

Figure 21. Aster yellows causes dark streaking or discoloration of wrapper.

Figure 22. Blasting of flowers occurs with aster yellows if scapes are left on.

HOW TO IDENTIFY Laboratory test to confirm.

CONTROL MEASURES Do not plant infected seed, reduce/eliminate perennial weeds, protect plants by spraying with pyrethroid insecticide when aster leafhoppers are present. Alternatively, use light colored or reflective mulches to disorient leafhoppers, or use floating row cover on seed crop from the beginning of the season.

PREVALENCE IN MINNESOTA AYP can be a major problem in Minnesota. The first severe outbreak was recorded in 2012. A moderate infestation occurred in 2021, and growers saw some crop losses. Leafhoppers appeared later in season in 2021 (June) and still caused crop losses, but not to the extremes as in 2012 when they arrived in April. There was some carryover in seed stock into 2022. There are few leafhoppers that overwinter in Minnesota. Most overwinter in southern states and then are carried to Minnesota by weather systems. Aster Yellows phytoplasma will survive and overwinter in the crown and roots of infected perennial plants, but not in plant debris.

White rot (Stromatina cepivorum)

WHAT IT IS Fungal disease.

SYMPTOMS Premature yellowing and dying of older leaves, stunting and leaf tipburn, followed by destruction of the root system, shoot dieback, and rotting of the bulb.

HOW TO IDENTIFY Laboratory test to confirm (looks very similar to Garlic Bloat Nematode).

CONTROL MEASURES Rotating out of allium crops for many years (white rot has been known to persist in soil for ten years), destroying infected tissue, and planting disease-free seed stock.

PREVALENCE IN MINNESOTA Uncommon in Minnesota, but it is a major disease of commercial garlic grown in California and other areas of allium production. The organism is most active when the temperature is cool (less than 75˚F). In northern climates it usually attacks in the spring.

Fusarium - basal or bottom rot (*Fusarium spp.*)

WHAT IT IS A fungus present in most soils. Usually considered a secondary invader because it attacks plants already weakened by insects, mechanical damage, or other diseases.

SYMPTOMS Similar to white rot, except disease progression is much slower and death of the plant may not occur. Yellowing of older leaves first (Figure 23) and rotting of the basal plate (Figure 24). Bulbs infected with fusarium may decay further in storage.

HOW TO IDENTIFY Laboratory test to confirm.

CONTROL MEASURES This disease is controlled by proper crop rotation with non-susceptible crops for four years, removal of infected plants, and planting disease-free seed. Plant in well drained areas. Common but only occasionally causes significant reduction in yield or marketability.

PREVALENCE IN MINNESOTA Present in most soils.

Figure 23. Fusarium causes older leaves to yellow.

Figure 24. Fusarium affects the basal plate.

Pink Root (Phoma terrestris)

WHAT IT IS Fungal infection.

SYMPTOMS Symptoms of this disease occur primarily in warm weather (>75˚F F). The fungus infects the roots, causing them to turn pink, followed by root dieback. New roots are formed which also become infected. Aboveground symptoms include leaf tipburn.

HOW TO IDENTIFY Lab test to confirm

CONTROL MEASURES Three- to four-year rotation without alliums.

PREVALENCE IN MINNESOTA Not common.

Botrytis (Botrytis spp.)

WHAT IT IS A fungus that attacks garlic leaves following periods of warm, wet weather, and bulbs in storage.

SYMPTOMS Water-soaked stems (which is why the disease is often called "neckrot".) In severe infections, the bulbs may rot. In mild infections, the disease may not be noticed during the season, but may attack the bulb during storage.

HOW TO IDENTIFY Lab tests to confirm

CONTROL MEASURES Promoting air movement by controlling weeds and proper plant spacing throughout the field so that foliage does not remain wet. Rapid drying during harvest, followed by good aeration during storage will also minimize the problem. Use planting stock free of the disease.

PREVALENCE IN MINNESOTA While the fungus itself is common, this is not usually a serious issue. More of a concern in wet years.

Skin Blotch (Embellisia allii)

WHAT IT IS Fungal infection.

SYMPTOMS Normally superficial and feeds on dead tissue, but can penetrate into bulbs and cause more significant damage if left unchecked.

HOW TO IDENTIFY Characteristic black or gray blotches on bulb or stem after harvest (Figure 25).

CONTROL MEASURES Increase air flow and reduce humidity during curing and storage. Removal of outer skins after drying can reduce or eliminate blotches.

PREVALENCE IN MINNESOTA Common, especially in wet years and when stored under humid conditions.

Figure 25. Fungal infections can cause black or gray blotches on bulb or stem.

Penicillium molds *(Penicillium spp.)*

WHAT IT IS Fungus.

SYMPTOMS Plants from infected cloves planted in the fall will often emerge in the spring, turn yellow, and then die. A blue-green color is observed on cloves in soil and in storage (Figure 26).

HOW TO IDENTIFY Symptoms on leaves look similar to fusarium, use laboratory tests to confirm and look for blue-green color on cloves. Can be confirmed by a lab test.

CONTROL MEASURES If a bulb is infected, do not use the cloves for planting stock. Wash hands after touching the bulb and avoid bruising or wounding stored bulbs. Prevent the disease by planting clean stock.

PREVALENCE IN MINNESOTA Present in most soils.

Figure 26. Penicillium molds cause a blue-green color on garlic.

Anthracnose (Colletotrichum fioriniae)

WHAT IT IS Fungal disease that affects garlic scapes.

SYMPTOMS Tan or orange colored lesions located on the scape that lead to twisting, girdling and collapse of scape (Figures 27 and 28).

Figure 27. Anthracnose causes tan or orange colored lesions located on the scape

Figure 28. Anthracnose can lead to collapse of scape.

HOW TO IDENTIFY Symptoms and lab test to confirm.

CONTROL MEASURES Difficult to control in wet weather. Do not over irrigate.

PREVALENCE IN MINNESOTA The fungus is most prevalent during wet years and incidence is greatest following scape removal, but still may occur with scape still on the plant.

Rust (Puccinia allii)

WHAT IT IS Fungal infection.

SYMPTOMS Initial symptoms occur on the foliage and stem as small, white flecks that develop into orange spots (spores) or pustules. The bulbs become shrunken and deformed. Heavily infected plants may turn yellow and die.

HOW TO IDENTIFY Red/orange pustules on leaves and stem (Figure 29).

Figure 29. Red/orange pustules on leaves and stem are caused by rust fungal infection.

CONTROL MEASURES Conditions favorable for disease development include high humidity and low rainfall and a temperature between 45 and 55 degrees Fahrenheit. Disease incidence is highest in stressed plants. To reduce infection potential, use healthy seed in well-drained soil. Rotate with non-allium crops. Registered preventive fungicides may be the only method of control in situations where the disease potential/incidence is high. Varietal resistance has not been reported.

PREVALENCE IN MINNESOTA Until recently, this fungus was considered to be of minor importance in garlic production. However, outbreaks in California have reduced crop yields by up to 75 percent in some fields. The disease has been reported in Minnesota but damage has been minor.

Virus - Potyvirus, Mosaic virus

WHAT IT IS Virus, Transmitted by aphids.

SYMPTOMS Usually none, but can cause severe leaf mosaic when in combination with other viruses (Figure 30).

HOW TO IDENTIFY Virus can be identified in the lab using molecular and serological tests.

CONTROL MEASURES Tissue culture has been shown to be effective in producing "virus-free" garlic and is now used extensively for commercial plantings in California. Any plants exhibiting severe mosaic symptoms should be rogued out. Most of the garlic purchased from seed catalogs and other garlic growers contains some virus.

PREVALENCE IN MINNESOTA Because garlic is clonally propagated, almost all planting stock is infected with some type of virus. The viruses are usually mild and do not seriously affect yield, and may even impart desirable characteristics in some varieties. One exception is onion yellow dwarf virus, which can cause severe mosaic in combination with other viruses.

Figure 30. Garlic leaf mosaic.

Mites

Garlic Mites (Rhizoglyphus spp. or Aceria spp.)

https://www.sfa-mn.org/wp-content/uploads/2020/02/bulb_mites_garlic.pdf

WHAT IT IS Tiny arachnids that are not visible to the unaided eye. Often referred to as either "dry bulb mites" if in the Aceria genus or simply the standard "bulb mite" in the Rhizoglyphus genus.

SYMPTOMS Failure to germinate or lack of vigor with stunted, deformed leaves. Feeding on the basal plate (Figure 31) can cause wounding and infection with Fusarium or Penicillium. It is possible that plants survive and outgrow damage. Mites will continue to feed on bulbs in storage. In storage, look for sunken tan to brown spots on cloves (Figure 32). Dry bulb mites can transmit allexiviruses.

Figure 31. A garlic bulb wounded by mite feeding in the field.

Figure 32. A garlic bulb wounded by mite feeding in storage.

HOW TO IDENTIFY Mites have 4 pairs of legs and are about 0.5-1 mm in length. Bodies are whitish to yellow. A hand lens or microscope is helpful for identification.

CONTROL MEASURES Do not plant infected seed; rotate alliums out for at least four years and control wild allium species in each field. Mites can survive on crop residue. Avoid planting garlic following brassicas, corn, grain, or grass cover crops; Treat seed before planting by:

- Soaking for 24 hours in 2% soap (not detergent) and 2% mineral oil
- Dusting bulbs with sulfur
- Hot water treatment is effective but may reduce germination (130˚F 10-20 minutes, or 140˚F for 10-15 minutes)

PREVALENCE IN MINNESOTA Incidence of mite damage has been recorded in Minnesota garlic. Some years appear to be more damaging than others and may be related to an infected seed source.

Insects

Allium Leaf Miner - (*Phytomyza gymnostoma*)

WHAT IT IS Insect-fly Symptoms: Larvae are the most destructive phase of the insect, eating soft tissue of plants as they mine down toward the bulb. This weakens plants and leaves them susceptible to secondary fungal infections and bacterial rot.

HOW TO IDENTIFY The adult allium leaf miner fly is ⅛ inch long and mostly black with distinctive orange patches on the head. Can be identified on the garlic plant by looking for slits in leaves from where the female deposits eggs which look like white dots.

CONTROL MEASURES There is no treatment available after infection, so preventative measures are important. Rotate garlic to a field without alliums for at least one year. Cover cropping with collards, mustard, cabbage, rapeseed, or daikon. Avoid high nitrogen fertilizer. Row cover (fine-mesh) is one of the most effective ways of preventing infection.

PREVALENCE IN MINNESOTA Leafminers have not been reported in Minnesota, but have been found in the eastern US and are moving west.

Wireworms (several genera)

WHAT IT IS Beetle larvae.

SYMPTOMS Damage to roots and bulbs. Usually one or two holes bored into bulbs.

HOW TO IDENTIFY Yellow/brown beetle larvae ½" to 1½" long.

CONTROL MEASURES Wireworms are more common if garlic is planted into fields following sod, so the best control is to avoid planting garlic following sod. Allow at least one year after sod is turned under before planting garlic.

PREVALENCE IN MINNESOTA Common, but only occasionally cause significant reduction in yield or marketability; infestations often limited to a few larval aggregations in a given field.

Onion Thrips (*Thrips tabaci*)

WHAT IT IS Small, sucking insects that are most prevalent during warm, dry weather.

SYMPTOMS whitish specks on the leaves, which become blotchy or scarred in severe cases.

HOW TO IDENTIFY most thrips are about 1 mm in length.

CONTROL MEASURES Use of insecticidal soaps will help to control the pest and a few chemical insecticides, such as the organic-certified pyrethrins (e.g, Pyganic), are also available for control.

PREVALENCE IN MINNESOTA Common, however the small, sucking insects are most prevalent during warm, dry weather.

Onion maggot (*Delia antiqua*)

WHAT IT IS White larvae of the onion fly.

SYMPTOMS Young garlic plants yellow and wilt; base of the plant may rot due to feeding damage; includes direct feeding damage on the bulb.

HOW TO IDENTIFY White larvae, about one millimeter in length soon after hatching, usually found at the base of the plant. They grow to about five millimeters after about 15 to 20 days.

CONTROL MEASURES Yellowed plants should be removed immediately and discarded. Control this pest through proper rotation. Do not plant garlic after onions or other alliums.

PREVALENCE IN MINNESOTA Although the maggot can complete two to three generations per year in the Midwest, maggot pressure and damage is highest in the spring. Onion maggots are present but not common.

Armyworms

WHAT IT IS The two most common species in Minnesota include the True and Fall armyworms. True armyworm ((*Pseudaletia unipuncta*) caterpillars will often have yellow to cream, or orange stripes down the side, with orange heads. Fall armyworms (*Spodoptera frugiperda*) range from brown to gray, green, or yellow-green in color with a whitish inverted Y shape between the eyes and three whitish stripes behind the head.

SYMPTOMS Defoliation of leaves can occur quickly following a high influx of moths and egg-lay

HOW TO IDENTIFY Eggs are laid in large, fuzzy masses, and many larvae can feed on a given plant, often on the upper leaves.

CONTROL MEASURES If high populations exist and damage occurs, the insect can be controlled by using Bt (*Bacillus thuringiensis*) sprays; however, only the young (early instar) larvae are most susceptible to Bt (e.g., larvae < ¼" length). Another insecticide registered for leaf-eating caterpillars on garlic includes spinosad (Entrust SC), certified for organic growers.

PREVALENCE IN MINNESOTA Both the true and fall armyworm are common in the upper Midwest. True armyworm is active in June, while fall armyworm migrates from southern states in July and August. Once a plant is defoliated, larvae will move in mass to the next available plant. Not generally a major problem in Minnesota garlic.

Other

Waxy Breakdown

WHAT IT IS Physiological condition not due to infection by microorganisms.

SYMPTOMS Cloves shrink and turn yellow and waxy inside the bulb. Bulbs sometimes become pasty or gelatinous or sometimes turn hard.

HOW TO IDENTIFY Symptoms.

CONTROL MEASURES Cause is unknown, but it has been suggested that it may be due to high temperatures during growth and/or after harvest or poor ventilation and low oxygen levels during storage.

PREVALENCE IN MINNESOTA Not highly prevalent but present.

Harvesting and curing

Knowing when to harvest has always been tricky. In general, garlic harvest in Minnesota usually extends from the second week of July through the first week in August. Different varieties will often mature at different times. Harvesting too early will result in small bulbs that do not store well. Harvesting too late will force the cloves to pop out of the skins, making them susceptible to disease and resulting in unmarketable bulbs. There are a couple of methods that can be used to determine when to harvest:

1) by early July the lower leaves will start to brown, and harvest is usually optimum when half or slightly more than half of the leaves remain green; or when a third of the leaves at the bottom have gone brown or yellow.

2) pull a few bulbs and cut them in half; if the cloves fill the skins, then the bulbs are ready to harvest.

To harvest, the bulbs should be dug with the shoots and roots still attached. At this point there is some controversy about whether the bulbs should be washed. For some soils it is easiest to wash the bulbs the day of harvest and allow them to cure for a few weeks. Some growers feel that washing the bulbs may lead to more storage diseases such as skin blotch. The alternative to washing the bulbs after harvest is to let the plants cure for three to four weeks and then brush the soil off after curing. This latter approach is less time-consuming in the short run, but can be more time-consuming in the long run if the soil is high in clay content.

For larger plantings of garlic, mechanical implements are available. A few growers in Minnesota have been using harvest implements such as modified potato/carrot diggers and other types of undercutting equipment. Such equipment is available, though at the scale that most growers are operating in Minnesota, the cost for such equipment is high.

Figure 33. Garlic should be dried in a well-ventilated room with indirect light.

After digging the plants, they should be dried in a well-ventilated room (Figure 33). There are a multitude of methods employed by growers to structure the curing process. The most important elements are air flow/ventilation (ultimate goal is that each bulb is getting air flow), in indirect light (avoid exposure to direct sunlight, over-drying or complete darkness, as this increases the likelihood of mold). Some growers accelerate the curing process by using dehumidifiers or air conditioning units, but care must be taken not to dehydrate the bulbs. The goal is to dry outer wrappers while keeping the cloves moist. One way to determine if curing is complete is to clip the stem at 1-2 inches above the top of the cloves, and if no liquid oozes out, the process is complete. Some growers believe that in order to produce a premium quality bulb, it is important to leave roots and stems on during curing, but other growers do not have the space. After about three to four weeks of curing, the shoots and roots should have dried down. The tops should then be cut about one-half to one inch above the main bulb and roots should be trimmed close to the base of the bulb. Clean bulbs by removing only the outermost skins, being careful not to expose any cloves. Any remaining soil should be brushed away. Bulbs can be graded into the following diameter sizes: less than 2 inches, 2 to 2.5 inches, 2.5 to 3 inches, and more than 3 inches. Premium bulbs are those 2.5 inches and larger.

Storage

Optimum storage conditions will depend on whether the garlic is to be used for table stock or planting stock.

Table stock garlic is best stored at 32˚-40˚ F and a relative humidity of 60-70%, but as soon as you take it out of refrigeration, it declines rapidly. Table stock garlic also can be stored at room temperature and 60-70% relative humidity with indirect light, but will dehydrate faster than if stored at 32˚-40˚ F. Storage at relative humidity greater than 70% tends to promote rooting and can lead to development of molds. Softneck garlic typically can be stored for six to eight months at room temperature, while hardneck garlic usually starts to deteriorate after about three to four months. At 32˚ F, hardneck garlic can be stored for up to seven months without significant dehydration. Temperatures between 42˚-52˚ F will cause sprouting, and humidity greater than 70% tends to promote rooting.

Because it will not be stored for very long before planting, "seed" garlic should be stored at room temperature and 60-70% relative humidity with some airflow, and should not be stored in complete darkness.

Sources for garlic seed

Seed garlic may be purchased from various vendors listed on the SFA garlic webpage, the Minnesota Grown Directory, or from vendors selling garlic online, at Minnesota Garlic Festival, and at regional farmers markets.

Further reading

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Useful web pages

Sustainable Farming Association's Garlic Production & Marketing Resources: https://www.sfa-mn.org/garlic-resources/

Learn about a SARE study on garlic diversity: http://www.garlicseedfoundation.info/bigNewsforGarlic.htm

First Reports of Garlic Diseases in Minnesota:

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Extension webinar: Growing Great Garlic in Minnesota for Gardeners https://www.youtube.com/watch?v=DZ8yRiVx0HU

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Figure 1: Drawing by Amy Sparks.

Figure 17 & 18: Brett Arenz

Figure 24: B. Caine and C. Swett, Swettlab at UC Davis.

Figure 33: Jerry Ford