1.5

Irrigation–Principles and Practices

Introduction: Irrigation

UNIT OVERVIEW

Effective irrigation practices can improve yields and quality, minimize water use, and protect natural resources. This unit introduces students to the basic concepts, tools, and skills used to deliver water efficiently and effectively on both a field and garden scale. Students will learn about the role of irrigation water in agriculture, the movement and cycling of water in agricultural systems, and the environmental factors that influence the type, frequency, and duration of irrigation.

Two lectures and two demonstrations introduce the resources and essential skills needed to determine the proper timing and volume of irrigation. The first lecture covers basic irrigation concepts and terminology. The second lecture addresses the use of both quantitative (water budget and soil moisture sensors) and qualitative (feel) approaches to determine irrigation timing, outlines environmental factors that influence irrigation decisions, and describes irrigation delivery systems. Through exercises and problem solving, students will practice calculating water budgets used to develop irrigation schedules and determine total water volume needs per unit of time. The latter calculations will help the student determine needed irrigation delivery systems. Supplements to the lectures offer additional information on using the water budget approach to manage irrigation efficiently, along with details on water sensor technologies, dry farming techniques, and health and environmental impacts of nitrates contamination.

MODES OF INSTRUCTION

> LECTURES (2 LECTURES, 1 –1.5 HOURS)

Lecture 1 covers the role of irrigation water along with irrigation concepts and terminology. It finishes with a brief overview of differences and similarities between garden- and field-scale irrigation.

Lecture 2 focuses on techniques used to determining when to irrigate and how much water to apply. Note: If possible, have soil at different moisture levels available to demonstrate the "feel" approach to judging soil moisture.

> DEMONSTRATION 1: FIELD-SCALE IRRIGATION (2 HOURS)

This field-scale demonstration illustrates how to gauge soil moisture by feel and how to establish, use, and maintain field-scale irrigation equipment.

> DEMONSTRATION 2: GARDEN-SCALE IRRIGATION (2 HOURS)

This garden-scale demonstration illustrates how to gauge soil moisture by feel and how to establish, use, and maintain garden-scale irrigation equipment.

> EXERCISES 1–3: FIELD- AND GARDEN-SCALE IRRIGATION SAMPLE CALCULATIONS (0.5 HOUR EACH)

Given evapotranspiration information and output data for drip and sprinkler irrigation systems, students will review how to calculate the needed frequency and duration of irrigation for a 1-acre field and a 100-square-foot garden bed.

> EXERCISE 4: CALCULATING A WATER BUDGET FOR A ONE-ACRE BLOCK OF VEGETABLES (0.5 HOUR)

Students will use their region's evapotranspiration information to calculate the needed frequency and duration of irrigation for a 1-acre field.

> EXERCISES 5–6: HOW MUCH WATER DO I NEED? HOW MANY ACRES CAN I IRRIGATE? SAMPLE CALCULATIONS (0.5 HOUR EACH)

Students will practice calculating total water volume needs per unit of time to determine the need for irrigation infrastructure.

> ASSESSMENT QUESTIONS (0.5 HOUR)

Assessment questions reinforce key unit concepts and skills.

> POWERPOINT

See *casfs.ucsc.edu/about/publications* and click on Teaching Organic Farming & Gardening.

LEARNING OBJECTIVES

CONCEPTS

- The role of irrigation water in agricultural systems
- The movement and cycling of water in agricultural systems: E.g., transpiration, capillary action, evaporation, evapotranspiration, evapotranspiration rate, percolation
- Water quantity measurements: E.g., acre/feet, acre/inch, one hundred cubic feet (CCF), gallons/minute (GPM)
- Relevant measurements of soil moisture: Soil saturation, gravitational water, field capacity, permanent wilting point
- Environmental factors that influence the type, frequency, and duration of irrigation
- Different way to determine the need for irrigation: qualitative (feel method) and quantitative (water budgeting, soil moisture sensors)

SKILLS

- How to determine the timing and volume of irrigation using qualitative approaches: Gauging relative measures of field capacity using the feel method
- How to determine the timing and volume of irrigation using quantitative approaches: Water budgeting calculations using evapotranspiration rates and calibrated water delivery systems
- How to calculate total water volume needs per unit of time to determine the need for irrigation infrastructure
- How to access web-based irrigation information
- How to determine the appropriate irrigation delivery system to use for specific crops and settings

Lecture 1: Irrigation—Concepts & Terminology

Pre-Assessment Questions

1. Why is water important for growing crops?
2. How is water volume commonly measured in agricultural systems?
3. How does irrigation water cycle through an agricultural system?
4. How does water stress negatively affect crop development and yield?

A. The Role of Irrigation Water in Agriculture Systems

1. Sustains soil biological and chemical activity and mineralization during dry periods: In seasonally dry areas, irrigation water artificially extends the time period in which soil biological activity and nutrient release are elevated, creating more optimal growing conditions for cultivated crops
2. Promotes soil solution and nutrient uptake: Irrigation water becomes the medium into which soil nutrients are dissolved (soil solution) and through which nutrients are made available for plant uptake
3. Provides carbohydrate building block: $6\ CO_2 + 6\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ O_2$: Through the process of photosynthesis, water molecules taken up by plants are broken down and their constituent atoms rearranged to form new molecules: carbohydrates and oxygen
4. Provides plant structure/support: Water molecules contained within the water-conducting vascular bundles and other tissues of plants serve to provide physical support for the plant itself
5. Promotes the maintenance of optimal temperatures within the plant: The loss of water through the process of evapotranspiration (defined below) liberates heat from the plant, thereby regulating plant temperature
6. Protects crops from frost damage: Irrigation water is commonly used to lower the freezing temperature in orchard systems during threats of damaging frost
7. Reduces plant stress: By reducing stress on the plant, proper irrigation improves plants' resistance to pest and disease damage and improves crop quality (see E, below)

B. Water Cycling in Agricultural Systems

1. Definition of terms (see also Appendix 1, Water Cycling Terms)
   a) Transpiration: Water transfer to the air through plant tissues.
   b) Evaporation: The loss of water to the atmosphere from soil and plant surfaces
   c) Evapotranspiration: The loss of water to the atmosphere by the combined processes of evaporation and transpiration (see more at Supplement 1, Evapotranspiration (ET) and the Factors that Affect ET Rates)
   d) Capillary action: The movement of water through very small pores in the soil from wetter areas to drier areas. Water may move vertically and horizontally.
   e) Infiltration: The process by which water on the ground surface enters the soil
   f) Percolation: The gravitational process of water moving downward and through the soil horizons

C. Units of Water Measurement

1. Definition of terms
   a) Acre inch: The equivalent volume of water application that would cover one acre of land one inch deep in water. Example: On average, approximately one inch of water is lost through evaporation and plant transpiration each week from May 15th–October 15 along the central coast of California (see Appendix 2, Units of Water Measurement)
   b) Acre foot: The equivalent volume of water application that would cover one acre of land one foot deep in water
   c) Gallons per minute (GPM): The number of gallons being delivered through an irrigation system in one minute
   d) One hundred Cubic Feet (CCF): Term commonly used by municipal water providers as a means of water measurement based on volume. 1 CCF equals 748 gallons.
   e) Pounds per square inch (PSI): Water pressure in irrigation systems is measured in PSI. Determining your irrigation system's specific PSI is important in irrigation planning.
   f) Distribution Uniformity (DU): A measure of how uniformly water is applied to the area being irrigated, expressed as a percentage. The higher the DU percentage, the more uniform the application. See Appendix 3, Calculating Distribution Uniformity, for additional information.

D. Overview of Garden vs. Field-Scale Irrigation (to be further discussed in Lecture 2, Irrigation Scheduling and Delivery Systems)

1. Features of garden- and field-scale cropping systems that influence irrigation
   a) Gardens: Smaller, more diverse, hand cultivated
   b) Garden irrigation water sources
      i. Domestic wells with 2 to 5 horsepower submersible pumps (10 gal/minute average output)
      ii. Municipal water systems (for urban gardens)
   c) Fields: Larger blocks of plantings, mechanically cultivated
   d) Field irrigation water sources; note—minimum 10 gal/acre/minute recommended
      i. Agricultural wells (10 horse power or larger electric or diesel pumps / 50 gallons per minute minimum)
      ii. Surface sources supplemental to well water (ponds, creeks)
      iii. Water district deliveries from surface sources supplied through canals or pipe lines
2. Similarities in irrigation scheduling and delivery systems between the two settings
   a) Whether operating on a garden scale or field scale, irrigation managers need to make decisions about water application rates and type of delivery based on crop needs, weed management, disease potential, evapotranspiration (ET) rates, and harvest schedules while using both labor and water wisely and efficiently.
3. Differences in irrigation scheduling between the two settings
   a) Garden scale: Typically use "soil moisture by feel" (qualitative) approach to determine need for irrigation, as well as scheduling and reference to local ET rates (see Lecture 2 and Appendix 4, Estimating Soil Moisture by Feel)
   b) Field scale: Typically use water budgeting (quantitative) approach along with tensiometers or other moisture monitoring devices to determine need for irrigation (see more at Lecture 2, as well as Supplement 2, Overview of "Water Budget" Approach for Efficient Irrigation Management, and Supplement 3, Soil Moisture Sensing Instruments Commonly Used for Irrigation Schedules)

Lecture 2: Irrigation Scheduling & Delivery Systems

Pre-Assessment Questions

1. How do you determine when it is time to irrigate?
2. What is the fundamental difference between a qualitative (by feel) and quantitative (water budget, soil moisture meter) approach to determining when to irrigate?
3. How do you determine how much water to apply?
4. What are some of the environmental factors that may influence the frequency or duration of irrigation?
5. What are some of the environmental factors that may influence the type of irrigation used?
6. What are some of the different irrigation delivery systems available?

A. Definitions of Terms Specific to Soil Moisture Assessment (see also illustrations in Appendix 1, Water Cycling Terms)

1. A number of terms are used when discussing the amount of moisture in the soil and plant's ability to access that moisture
   a) Soil saturation: When all the pores of a given soil are filled with water. Soil rarely remains saturated once watering (rain or irrigation) stops because gravitational water percolates (drains) down to deeper soil strata.
   b) Gravitational water: The water that will drain from a saturated soil if no additional water is added. This water is not available for plant growth.
   c) 100% of field capacity: The point reached when no additional gravitational water drains from a previously saturated soil. At 100% field capacity the largest pores of the soil structure (macropores) have been drained of water and replaced with air, while micropores still retain water. This water is available to plants, which have the ability to move water against gravity due to the upward pulling force produced by transpiration. At field capacity, an improved soil retains the maximum amount of water available to plants, as well as optimal air space for aerobic microbial activity and plant growth.
   d) 50% of field capacity: The amount of water remaining in the soil when 1/2 of the water held in the soil at field capacity has evaporated, drained, and/or has been transpired by growing plants; 50%–60% of field capacity in the root zone of the crop is the soil moisture level at which most crops should be irrigated
   e) Permanent wilting point (PWP): The point at which soil moisture has been reduced to where the plant cannot absorb it fast enough to grow or stay alive
   f) Plant available water (PAW): The water content held in the soil between field capacity and permanent wilting point that is available for uptake by plants
   g) Soil water potential: The amount of energy required to remove water from the soil. This measurement increases as soils dry, which then increases the possibility of transpiration rates exceeding the rate of uptake, leading to plant stress.
   h) Management allowable depletion (MAD): Maximum amount of soil water the irrigation manager allows the crop to extract from the active rooting zone between irrigations. This amount can vary with crop, stage of growth, potential for rainfall, and the soil's water holding capacity.

B. Soil Moisture, Plant Stress, and Crop Productivity

1. Yield may be reduced due to water stress
   a) Water-stress-sensitive stages of crop development (prioritized); see also Appendix 5, Critical Periods for Soil Water Stress by Crop
      i. Flowering
      ii. Yield formation/fruit set
      iii. Early vegetative growth/seedling stage
      iv. Fruit ripening
2. General signs of water stress
   Plants can show some water stress and still recover—however, extreme lack of water will cause permanent wilting (see below) and death. Signs of water stress include:
   a) Graying leaves: A change in leaf color from a vibrant green to a dull gray-green or bluish color
   b) Loss of sheen: Plant leaves change from glossy to dull in appearance
   c) Insect damage: The presence of cabbage aphids on Brassica family crops (broccoli, cabbage, kohlrabi, etc.) often indicates dry conditions
   d) Damage to the root system: Upon closer examination, plants that look dry even after watering often have root damage, e.g., from symphylans, and can't take up sufficient water
   e) Red or purple leaf color: Can indicate dry conditions, saturated conditions (anaerobic), or root damage
   f) Development of small spines on the leaf margins or increased spinyness on stems: This condition is especially likely to occur in lettuce and related species such as endive that experience water stress
   g) Wilting: Pay attention to the time of the day. If plants wilt early in the cool of the day, this can be a sign that they need water. Some wilting in the mid-day heat (e.g., zucchini, winter squash) is a plant-protective strategy to reduce transpiration losses.
   h) Slower than expected growth: This can be detected over time with a practiced eye
3. Water stress increases crops' susceptibility to pests and pathogens

   Crops repeatedly subjected to water stress will be less resistant to both pest and pathogens
4. Permanent wilting point

   Permanent wilting point is defined as the point at which soil moisture is too low for the plant to take up water against the pull of gravity. Crop plants reaching permanent wilting point often do not grow well thereafter, are non-productive, or die.

C. Factors Influencing Frequency and Volume of Irrigation

A number of factors, from climate and soil type to stage of crop maturity, must be considered in determining when and how much to irrigate. Factors include:

1. Climate
   a) Air temperature: Increased air temperatures will increase the rate of evapotranspiration (ET)
   b) Precipitation: In areas of regular summer rainfall, where precipitation exceeds ET, irrigation is seldom required. Irrigation demands are based on ET rates. Where ET exceeds precipitation, irrigation is required.
   c) Humidity: Increased humidity will decrease the rate of ET
   d) Wind: High wind speeds increase ET

2. Soils
   a) Sandy soils drain rapidly and do not hold water well
   b) Silty soils drain slowly and hold water well
   c) Clay soils drain very slowly and hold water tightly
   d) Loam soils both drain well and hold water well
   e) Agricultural soils improved with organic matter (cover crops, compost) maintain good drainage and moisture retention properties (for more on this topic, see discussion in Unit 1.6, Selecting and Using Cover Crops and Unit 1.7, Making and Using Compost)
3. Stage of development and crop natural history
   a) "Water-loving" crops (e.g., celery) demand less fluctuation in soil moisture levels (see Appendix 6, General Irrigation Rules, and Appendix 7, Irrigation for Various Vegetable Crops)
   b) Drought-tolerant crops (e.g., tomato varieties, winter squash varieties, Amaranth, etc.) may require little or no irrigation (see Supplement 4, Overview of Dry Farming on the Central California Coast)
   c) Maturation period: Prior to harvest, many crops (e.g., onions and garlic) require a gradual reduction in irrigation to encourage maturation
   d) The specific watering needs of tree fruits are highly variable, and depend on a combination of the tree's age and size, rootstock, and your soil and climate. In general, deciduous fruit trees need readily available moisture in the root zone through harvest to promote canopy development, extension growth, fruit sizing, and fruit maturation. This normally means letting the soil dry down to no more than 6–8" deep between irrigations and replacing water based on local ET rates to ensure high fruit quality.
   e) Citrus and other evergreen fruit trees also need regular water delivery for the same reasons noted above for deciduous fruit. In the case of citrus, which are often flowering, setting fruit, and maturing fruit simultaneously, consistent water delivery is important to maintain citrus tree health, vegetative vigor, and fruit quality. Both irrigation and rainfall should be monitored year round, and the soil should only be allowed to dry to a depth of 3–4", followed by an irrigation set to replace water lost to ET. Underwatering citrus as fruit ripens can lead to small fruit and dry, flaky interiors.
   f) Vase life of cut flowers can be improved—in some cases dramatically—by developing an irrigation schedule that delivers water to crops ready to harvest at least 12 hours but not more than 24 hours prior to harvest. This will help ensure that stems have full turgor and stress can be minimized, allowing stems to maintain turgor through post-harvest uptake rather than trying to compensate for an already extant water deficit. With reduced stress, plants will consume stored nutrients more slowly, extending the time that cut stems remain strong and vibrant.

D. Determining When to Irrigate and How Much Water to Apply

1. Measuring soil moisture by feel: A qualitative approach
   a) Measuring soil moisture by feel includes learning how to judge soil moisture by forming soil into a cast or ball, and by "ribboning" soil (see Appendix 4 and the NRCS publication *Estimating Soil Moisture by Feel and Appearance* noted in the Resources). This takes practice! Knowing the percent of soil moisture present can help determine whether irrigation is needed.
   b) Shovels, trowels, and soil augers can be used to obtain soil samples to a depth of up to 12 inches in the crop root zone for accurate moisture assessment (see illustrations in Appendix 8, Soil Auger and Soil Probe)

2. Considerations for determining irrigation scheduling using the "feel" approach
   a) The "feel" method is more commonly used by irrigation managers in garden and small farm systems as a low-tech, low-cost way to assess irrigation needs in diverse cropping systems
   b) Irrigation managers must be familiar with soil type and appropriate methods of soil moisture assessment to make accurate irrigation scheduling decisions
   c) The "feel" approach to irrigation management requires a high level of intuition and experience, and an extensive knowledge of the specific requirements of the various crops being irrigated. Once understood, it can be a quick decision-making tool.
   d) In deciding when and how much to irrigate, the irrigation manager must take into account a variety of factors in addition to soil moisture, including crop needs, and timing of harvest (see D. Factors Influencing Frequency and Volume of Irrigation, and below), as well as weed management operations to determine an optimum application time and rate
3. Determining irrigation scheduling using the water budget approach
   a) Water budgeting is often compared to managing a savings account: The starting point is field capacity (see definitions, above), and as water is removed and the "savings balance" drops, it is replaced as needed by the crop. Water budgeting is a quantitative approach using existing models that analyze temperature and crop water use to determine evapotranspiration (ET) rates. Growers use these models to determine irrigation timing and amounts.
   b) When seasonal ET exceeds precipitation, irrigation is required to sustain planted crops
   c) Resources for determining regional average ET (e.g., CIMIS; see Resources section); you can use this regional average when determining a water budget
   d) Replacing estimated water loss through ET with calibrated irrigation systems
      i. Once the ET rate of your site is determined, this estimated volume of water may be replaced through the use of calibrated irrigation systems that deliver water at a known rate and volume. The Hands-on Exercises in this unit offer examples of how to calculate the irrigation time and frequency required to replace water with a calibrated irrigation system.
   e) Irrigation scheduling in different systems based on water budgeting approach
      i. Once the evapotranspiration rate for a crop in full canopy (in gallons/week) and the water delivery rates (in gallons/hour) of the irrigation system are estimated, the amount of time required to replace water lost may be calculated (see Hands-On Exercises). This calculation will provide the total number of hours required to replace the water lost through evapotranspiration. (An additional 10% should be calculated in to compensate for delivery system inefficiencies.)
      ii. The frequency of irrigation should correspond to the time period required for the soil in the root zone of the crop to dry to approximately 50% of field capacity. Due to shallow root systems and greater susceptibility to water stress, annual crop culture often requires a higher frequency of irrigation (2–3 times/week for many crops).
      iii. Established orchards, which have deep root systems and are less susceptible to water stress, often require less frequent but larger volumes of water to be delivered in each irrigation. In both situations the estimated amount of water lost through ET is replaced as needed to maintain the health of the crop.

f) Once a decision is made to irrigate, and a volume is determined, the timing of the water application must take into account timing of future harvest and weed management operations

g) Disadvantages: Water budget approach is not easy to apply to small, diverse systems

h) Advantages: Water budget approach can be an effective tool to increase water use efficiency

4. Determining irrigation scheduling using tensiometers and other soil moisture sensors (see Supplement 3, Soil Moisture Sensing Instruments Commonly Used for Irrigation Schedules)

   a) As the cost of simple soil moisture sensors drops, many growers are beginning to incorporate these instruments in their systems to monitor soil moisture levels. Such devices provide site-specific data points that may be more accurate than CIMIS data and can be used in combination with other techniques to inform irrigation decisions.

      i. Soil tensiometers and Electrical Resistance Sensing Devices (ERSDs) are the instruments most commonly used to measure soil moisture on California's Central Coast farms. Both must be carefully installed directly in the wetted area of the crop's root zone at a number of sites throughout the field for accurate monitoring (see Supplement 3 for details).

      ii. Soil moisture sensors are often used in pairs at different depths, e.g., at 6 and 12 inches deep, to provide the irrigator with information on below-ground moisture dynamics

      iii. Tensiometers and ERSDs provide soil/water tension readings that can be used to establish irrigation schedules adequate to maintain soil moisture at levels conducive to good crop growth and productivity

5. Other factors to consider when determining whether irrigation is needed

   a) How do the plants look? See above for list of general signs of water stress.

   b) Weather patterns: E.g., a crop may look stressed at midday, but knowing that the weather will cool overnight and be foggy in the morning may mean that irrigation is not immediately required. Therefore observing the crops throughout the day is important.

   c) After a cool period, the first hot day may trigger plants to look stressed, but in fact they may not need irrigation

   d) Soil type: Soil type and organic matter levels will determine in part how the soil holds water (see the NRCS reference *Estimating Soil Moisture by Feel and Appearance* in References)

   e) Type of crop: Different crops, different needs (Appendix 7, Irrigation for Various Vegetable Crops)

   f) Stage of development: Some crops benefit from being slightly water stressed early in their growth cycle (e.g., tomatoes, beans, cucumbers and other cucurbits), or do not need irrigation once the plants begin to die back (e.g., potatoes). Others, particularly small-seeded crops such as lettuce and carrots, require that soils be kept moist in order to germinate effectively.

   g) Optimal moisture for harvest: It is critical to maintain full turgor for leafy crops and cut flowers, particularly if they will not immediately go into a cooler or receive some form of hydrocooling, as is done with brassicas and similar crops (see more at C. Factors Influencing Frequency and Volume of Irrigation, above)

E. Problems with Overapplying Water

1. In many areas, fresh water is a limited resource. Irrigation practices that optimize the available supply are critical.

2. The energy and environmental costs involved in transferring water and "lifting" it to irrigation systems via pumps, etc., can be significant

3. Over application of irrigation water has the potential to germinate weed seeds that would have otherwise remained dormant in the soil, leading to higher labor costs for weed removal and/or significant crop competition resulting in decreased yields
4. Overapplying water can lead to unnecessary nutrient leaching, soil compaction, decreased water infiltration rates, erosion, and nutrient leaching (see Supplement 5, Nitrate Contamination of Groundwater)

F. Irrigation Delivery Systems (see also Appendix 9, Irrigation System Components)

1. Sprinklers
   a) Micro sprinklers
      i. Micro sprinklers are commonly used in small-scale orchards and vineyards
      ii. Micro sprinklers are commonly used in garden-scale production systems that require frequent, light irrigation to help germinate small seeds
      iii. Micro sprinklers provide uniform application of water and the relatively small droplet size minimizes soil surface crusting and aggregate dispersion
      iv. Small droplet size is not optimal for distribution uniformity (DU) or water use efficiency in windy areas
   b) Hand-moved aluminum pipe with impact or rotator type heads
      i. Hand moved aluminum irrigation pipe is the most commonly used sprinkler irrigation delivery system in both small- and large-scale farming operations due to relatively low cost, long life, ease of use, and durability
      ii. Hand moved aluminum pipes typically use 3-inch diameter lateral lines with a 3-gallon-per-minute (GPM) sprinkler head mounted on an 18" riser on each 30' long section of pipe. Lateral lines are typically spaced either 30' or 40' feet apart.
      iii. Aluminum sprinkler pipes fitted with impact heads typically require an operating pressure of at least 45 psi for optimum uniformity. Rotator type heads require higher pressure.
   c) Hand-moved PVC "riser system" for garden-scale applications
      i. A simple-to-build, portable riser system of PVC and micro sprinklers can serve the same purpose as hand-moved aluminum pipe at a garden scale (see Appendix 9)
      ii. Because it has fixed spray patterns of 180º and 360º at a pre-determined distance, the riser system can be sized to suit your garden's scale and design, assuming basic irrigation knowledge and access to a standard irrigation supply store
      iii. The pattern and uniformity of distribution are relatively consistent and predictable, and the system can be run with minimal attention to water pressure
      iv. Spray distribution, while still gentle on surface soil structure, is delivered in relatively large drops and risers are only 15"–18" tall, so loss of uniformity and evaporation due to wind exposure is minimized
      v. The riser system can be used to germinate seeds, to grow overhead irrigation-loving or tolerant crops and low-growing crops to maturity, and can be used to pre-irrigate and flush weeds in smaller areas. In the absence of timely rains, the riser system can also be used to establish cover crops and until cover crop height exceeds the height of the risers.
   d) Oscillators
      i. Oscillating sprinklers are often used in garden settings, and are a relatively low-cost, easy-to-use water delivery system
      ii. Advantages of oscillators
         - Offer large degree of coverage size and pattern flexibility in a single unit

- Relatively low cost, readily available, and can be operated with little technical background
- Although vulnerable to the wind, oscillators may be useful when "rough irrigating" large blocks of garden beds, e.g., prior to planting cover crops, and when irrigating large garden spaces

iii. Drawbacks

- Relatively low uniformity of water distribution and high rates of evaporation, especially in hot and/or windy situations (see below for more on distribution uniformity, or DU)
- Can take time to adjust and "dial in" to provide full, even coverage of the desired area without also delivering water beyond the boundary of the desired irrigation set
- Inconsistent distribution pattern and vulnerability to wind redistribution; neighboring crops may be subject to "drift" and thus increased disease incidence if they are prone to fungal disease of the leaf canopy
- Can be difficult or time consuming to accurately determine output/distribution, thus leading to over- or underwatering. For example, the adjustability of oscillators means the same device could water a 4' x 12' section or a 30' x 30' section. So an irrigation set of the same duration will deliver very different amounts to these two garden plots.
- Quality of oscillator brands—their useful lifespan, adjustability, and distribution uniformity—varies widely, and it can be difficult to know quality until you've invested considerable time and energy

2. Drip irrigation

a) Drip irrigation has many advantages over sprinkler or flood irrigation, including application uniformity, the ability to apply water exactly where it is needed, and the potential reduction of disease and weed incidence in irrigated systems

b) Drip irrigation refers to both rigid ½ inch poly tubing with inline emitters and the thin wall tubing commonly referred to as "drip tape." Drip tape is available in an assortment of wall thicknesses and emitter spacings and is relatively low cost, but also much less durable compared to the rigid poly tubing.

c) Drip tape is commonly used in small-scale vegetable production systems as a means of conserving water and minimizing weed and disease pressure

d) Depending on the water source, drip tape and tubing often require filtration to limit clogging of emitters

e) Drip tape and poly tubing with inline emitters require pressure regulation to optimize application uniformity

f) Drip tape and poly tubing with inline emitters require a grade of 2% or less and runs of no more that 300 feet for optimum distribution uniformity

g) Careful consideration must be given to design when setting up a drip irrigation system to optimize distribution uniformity and system function

G. Environmental Factors Influencing the Type of Irrigation Used

1. Climate and incidence of plant pathogens (see also Unit 1.9, Managing Plant Pathogens)

a) Overhead irrigation may encourage the growth and spread of certain plant pathogens on crops in certain climates (e.g., *Phytopthora* spp. on melons, cucumber, peppers, and tomatoes along coastal California).

H. Importance of Distribution Uniformity (DU)

1. Distribution Uniformity (DU) refers to how uniformly water is made available to plants over an area via an overhead sprinkler or drip irrigation system
2. DU can be measured using a simple "catch bucket" test and the "low quarter DU" calculation for both overhead and sprinkler irrigation systems (see Appendix 3 for details). Note that measuring DU of oscillating sprinklers may require more catch buckets to accurately measure uniformity throughout the coverage area (corners, edges, and middles of beds).
3. It is important to maintain high DU in order to optimize water use and ensure that the entire crop is receiving the intended amount of irrigation

Demonstration 1: Field-Scale Irrigation

for the instructor

INTRODUCTION

This demonstration offers students an in-field look at the tools and techniques used to deliver irrigation water efficiently from the mainline irrigation infrastructure through the specific irrigation delivery system used on your farm. The instructor should begin with an explanation of the irrigation infrastructure used to deliver water to and through the farm, then explain how to set up, adjust, and maintain the specific irrigation system(s) currently in use.

PREPARATION AND MATERIALS

- Map of farm irrigation system

Irrigation equipment:

- Established set of aluminum pipe with sprinklers
- Component pieces of sprinklers
- Established set of drip irrigation
- Component pieces of drip irrigation equipment
- Tools for setting up and adjusting irrigation equipment
- Irrigation schedules (see Appendix 10, Field Irrigation Schedule)

PREPARATION TIME

1.5 hours

DEMONSTRATION TIME

2 hours

DEMONSTRATION OUTLINE

A. Irrigation Infrastructure

1. Explain the layout and identify major components of the farm irrigation water delivery system from source to crop

B. Measuring Flow Rate

1. Demonstrate how to determine flow rate using a garden hose and a 5-gallon bucket

C. Sprinkler Irrigation Systems

1. Demonstrate a typical field layout and a typical orchard layout of a hand-moved aluminum sprinkler system. Include the following demonstrations:
   a) The proper technique for moving and laying out sprinkler pipes
   b) Flushing the system clean
   c) Sprinkler head adjustment
   d) Layout design and pipe hook-up
2. Demonstrate and explain the importance of proper head adjustment and timing as it relates to application uniformity

3. Demonstrate and explain how to determine optimum operating pressure
4. Students are given the opportunity to unhook, move, and hook up a sprinkler set. The sprinkler set is then turned on and adjusted.

D. Drip Irrigation Systems

1. Demonstrate and explain several examples of drip irrigation header set-ups
2. Demonstrate and explain how to turn on a drip system and set pressure and check for leaks
3. Demonstrate the following:
   a) How a gate-valve and ball-valve work
   b) How to set up a drip irrigation header
      i. How to properly punch holes in the 2" oval tube
      ii. How to install the barbed connectors into the oval tube
      iii. How to connect the T-tape to the various types of connectors
      iv. How to splice T-tape for repairs
      v. How to cap ends of T-tape
      vi. How to determine proper system pressure
      vii. How to properly roll out and roll up T-tape for placement and storage
4. Have students cut and splice T-tape

E. Review and Discuss Irrigation Scheduling

1. Review the calculations in Hands-on Exercises 1–3 to determine the volume of water and the frequency of irrigation necessary to replace the water lost through regional evapotranspiration
2. Assign Exercise 4: Calculating irrigation requirements using regional evapotranspiration data
3. Describe and demonstrate the use of an irrigation schedule for tracking and planning irrigation (see Appendix 10)

F. Review and Discuss Exercises 5 and 6

1. Exercise 5: How much water is needed to irrigate a given area of land?
2. Exercise 6: How much area can one irrigate with a given flow rate?

G. Discuss water delivery systems needed to deliver the volumes of water given in Exercises 5 and 6

Demonstration 2: Garden-Scale Irrigation

for the instructor

OVERVIEW

Students must be able to accurately gauge soil moisture and use scale-appropriate irrigation tools and techniques in order to irrigate garden crops efficiently and effectively.

The following demonstration provides an overview of the basic skills, concepts, and tools used in garden-scale irrigation. During this demonstration, the instructor should discuss the different approaches to irrigation (qualitative and quantitative) as well as demonstrate the tools and techniques used to monitor soil moisture and schedule irrigation.

PREPARATION AND MATERIALS

- Drip irrigation system
- Oscillators
- Fan
- Rose
- Micro sprinklers
- Garden riser
- Rain gauge
- Ross
- Soil moisture chart (see Appendix 4, Estimating Soil Moisture by Feel)
- Blank irrigation schedule (see Appendix 11, Garden Irrigation Schedule)
- Soil samples or pre-irrigated soils at varying percentages of field capacity

PREPARATION TIME

1.5 hours

DEMONSTRATION TIME

2 hours

DEMONSTRATION OUTLINE

A. Irrigation Management by Percent Field Capacity

1. Review terms
   a) Soil saturation
   b) Gravitational water
   c) 100% of field capacity
   d) 50% of field capacity
      i. Review 50% of field capacity as critical moisture level for most cultivated annual crops
   e) 25% of field capacity
   f) Permanent wilting point
2. Review exceptions to the to the 50% field capacity general rule (see Appendix 6, General Irrigation Rules)
3. Review the stages of crop development at which plants are most sensitive to drought/ water stress (listed from most to least sensitive; see also Appendix 5, Critical Periods for Soil Water Stress by Crop)
   a) Flowering
   b) Yield formation/fruit set
   c) Early vegetative growth/seedling stage
   d) Fruit ripening
4. Have students gauge soil moisture (in percent field capacity) by feel and appearance using Appendix 4, and the USDA publication *Estimatng Soil Moisture by Feel and Appearance* (see Resources)
5. Review how to develop an irrigation schedule based on an estimated frequency of dry down to 50% of field capacity (see Appendices 11 and 12, Amount of Water Needed to Pre-Irrigate a Dry Soil to Different Depths)
6. Discuss and demonstrate how to properly maintain seedbed soil moisture for small- and large-seeded direct-sown crops
7. Discuss and demonstrate how to assemble, use, and repair garden-scale irrigation equipment (T-tape, oscillators, micro sprinklers, garden riser, etc.) in delivering water effectively and efficiently
8. Discuss and demonstrate how to assemble and repair the PVC portions of a garden-scale irrigation system

B. Irrigation Management Using the Water Budgeting Approach

1. Estimating crop Evapotranspiration (ET) loss from a crop in full canopy
   a) The use of California Irrigation Management Information Systems (CIMIS) data to determine average weekly ET (see Resources section)
2. Review and discuss the calculations used in developing a weekly irrigation schedule to replace water lost through estimated ET for drip-irrigated crops. Assign and review the Garden Irrigation Exercise (see next section).
3. Discuss and demonstrate the use of rain gauges in monitoring the volumes of water delivered to replace water losses through ET in overhead-irrigated crops. Note the issue and challenge of achieving an adequate level of distribution uniformity in using oscillators, and the importance of identifying areas (middle, ends, and corners of beds) that may be receiving too much or too little irrigation.

Hands-On Exercises 1–3: Sample Calculations—Replacing Water Lost through Evapotranspiration (ET) Using the Water Budgeting Approach

for the student

In Hands-on Exercises 1 through 3, you will see sample calculations for the amount of irrigation time and frequency of irrigations required to replace water lost through evapotranspiration (ET) from a 1-acre block of vegetables using drip irrigation and sprinkler irrigation, as well as a 100-square-foot garden bed (respectively).

EXERCISE 1

The following sample calculation will show you how to calculate the amount of irrigation time and frequency of irrigations required to replace the amount of water lost through evapotranspiration from a 1-acre block of vegetables in full canopy using drip irrigation.

A. NUMBER OF GALLONS LOST THROUGH EVAPOTRANSPIRATION (ET) IN A 1-ACRE FIELD

- Daily average summer evapotranspiration rate (ET) for an actively growing crop in full canopy in Santa Cruz = 0.15 inch/day
- Multiply this by 7 days/week = 1.05 inches/week
- There are 27,158 gallons of water in an acre inch (the volume of water needed to cover an acre of land to a 1-inch depth)
- An acre = 43,560 square feet (roughly 208 feet x 208 feet)
- Multiplying 1.05 inches/week (ET) x 27,158 gallons/acre inch = 28,516 gallons/acre of water lost each week through evapotranspiration in an actively growing crop in full canopy in Santa Cruz, California

B. DRIP IRRIGATION OUTPUT CALCULATIONS

- Flow rate of high flow T-tape drip irrigation ribbon with 8-inch emitter spacing at 10 pounds per square inch (psi) = .74 gallons/minute/100 feet
- There are 14,520 feet of row per acre when beds are spaced 36 inches center-to-center
- To determine gallons/hour/acre emitted from one acre of drip irrigation ribbon, divide 14,520 (the number of row feet/acre) by 100 = 145 (the number of 100-foot lengths of drip irrigation ribbon in 1 acre). Multiply 145 by .74 gallons/minute/100 feet (the amount of water delivered through each 100 feet of ribbon) = 107.4 gallons/minute/acre.
- 107.4 gallons/minute x 60 minutes = 6,446 gallons/hour/acre. Two lines of drip tape would provide twice this volume, or 12,892 gallons/hour/acre.

C. CALCULATING IRRIGATION REQUIREMENTS

- 28,516 gallons/acre are lost through evapotranspiration each week from an actively growing crop in full canopy. The drip system described above is capable of delivering 6,450 gallons/hour/acre @ 10 psi. To calculate the amount of irrigation time required to replace the amount of water lost through ET complete the following:
- Divide 28,516 gallons/acre (ET) by 6,450 gal/hour/acre (irrigation system application rate) = 4.4 hours of irrigation time required each week. Running the one acre of single line drip irrigation with 8 inch emitter spacing for 4.4 hours each week will apply 28,516 gallons/acre (~1.05 inches/acre), which is the amount of water needed to replace what is lost through ET. This total of 4.4 hours/week should be divided into 2–3 evenly timed irrigation sets.

EXERCISE 2

The following sample calculation will show you how to calculate the amount of irrigation time and frequency of irrigations required to replace the amount of water lost through evapotranspiration from a 1-acre block of vegetables using sprinkler irrigation.

A. NUMBER OF GALLONS LOST THROUGH EVAPOTRANSPIRATION (ET) IN A 1-ACRE FIELD

- Daily average summer evapotranspiration rate (ET) for an actively growing crop in full canopy in Santa Cruz = .15 inch/day
- Multiply this by 7 days/week = ~1.05 inches/week
- There are 27,158 gallons of water in an acre inch (an acre inch is the amount of water needed to cover an acre to a 1-inch depth)
- An acre = 43,560 square feet (roughly 208 feet x 208 feet)
- Multiplying 1.05 inches/week (ET) x 27,158 gallons/acre inch = 28,516 gallons/acre of water lost each week through evapotranspiration in an actively growing crop in full canopy in Santa Cruz, California.

B. SPRINKLER IRRIGATION OUTPUT CALCULATIONS

- Flow rate from a 1/8 inch nozzle running at an operating pressure of 45 psi is about 3 gallons per minute (gpm)
- There are roughly 109 sprinkler heads per acre using 20-foot pipes set 20 feet apart (20 feet x 20 feet = 400 square feet. 43,560 square feet/acre divided by 400 = 109)
- 109 sprinkler heads x 3 gpm each = 330 gallons per minute
- 330 gal/min x 60 minutes/hour = 19,800 gallons/hour/acre

C. CALCULATING IRRIGATION REQUIREMENTS:

- 28,516 gallons/acre are lost through evapotranspiration each week from an actively growing crop in full canopy. The sprinkler system is capable of delivering 19,800 gallons/hour/acre @ 45psi. To calculate the amount of irrigation time required to replace the amount of water lost through ET complete the following:
- Divide 28,516 gallons/acre (ET) by 19,800 gallons/hour/acre (irrigation system application rate) = 1.4 hours of irrigation time required each week.
- Running the one acre sprinkler system for 1.4 hours each week will apply 28,516 gallons/acre (~1.05 inches/acre), which is the amount of water needed to replace that lost through ET. This total of 1.4 hours/week should be divided in to 2–3 evenly timed irrigation sets/ week of 40 or 30 minutes respectively.

  *Note: It is also important to factor in an additional 10–20% for evaporative loss due to extreme heat and wind conditions. It is further advisable to use several rain gauges to check the actual amount applied and to assess uniformity of applications. See Appendix 2: Calculating Sprinkler and Drip Distribution Uniformity, for additional information.

D. CALCULATING AN ADDITIONAL 10−20% WOULD PROCEED AS FOLLOWS:

- 28,516 + 10% (.10 x 28,516) = 31,368 gallons/acre; 28,516 + 20% (.20 x 28,516) = 34,239 gallons/acre. Dividing each of the above by the irrigation system output results in the following: 31,368 gallons/acre divided by 19,800 gallons/hour/acre = 1.6 hours of irrigation time each week. 34,239 gallons/acre divided by 19,800 gal/hour/acre = 1.7 hours of irrigation time each week. These totals of 1.6 and 1.7 hours/week should also be divided into 2–3 irrigation sets each week for annual vegetables.

EXERCISE 3

The following sample calculation will show you how to calculate the amount of irrigation time and frequency of irrigations required to replace the amount of water lost through evapotranspiration from a 100-square-foot garden bed.

A. CALCULATING THE NUMBER OF GALLONS LOST THROUGH EVAPOTRANSPIRATION (ET) IN A 100-SQUARE-FOOT GARDEN BED

- Daily average summer evapotranspiration rate (ET) in Santa Cruz = 0.15 inch/day
- Multiply this by 7 days/week = 1.05 inches/week
- 25-foot x 4-foot garden bed = 100 square feet
- 100 square feet x 144 (square inches/foot) = 14,400 square inches
- 100 square feet to 1 inch in depth = 14,400 cubic inches
- 1,728 cubic inches/ cubic ft.
- 1 cubic foot = 7.48 gallons
- 14,400 cubic inches (100-square-foot garden bed) divided by 1,728 cubic inches = 8.33 cubic feet
- 8.33 cubic feet x 7.48 gallons/cubic foot = 62. 31 gallons/week lost through ET

B. DRIP IRRIGATION OUTPUT CALCULATIONS

- Flow rate of high flow T-tape irrigation ribbon with 8-inch emitter spacing @ 10 psi = .74 gallons/ minute/100 feet (assuming 100% efficiency)
- There are 133 emitters/100 ft @ 8-inch spacing
- .74 divided by 133 = 0.00556 gallons/minute/ emitter
- .00556 X 60 (inches/hour) = .334 gallons/hour/ emitter
- A 25-foot row of T-tape = 300 inches
- 300 inches divided by 8-inches emitter spacing = 37.5 emitters/row
- 37.5 emitters/row x 4 rows t-tape/bed = 150 emitters/ bed
- 150 x .334 gallons/hour/emitter = 50.1 gallons/ hour

C. CALCULATING IRRIGATION REQUIREMENTS

- 62.31 gallons of water are lost from a single 100-square-foot garden bed through evapotranspiration each week. Four lines of high flow T-tape deliver 50.1 gallons/hour @ 10 psi. To calculate the amount of irrigation time required to replace the amount of water lost through ET, complete the following:
- 62. 31 gallons/week (ET) divided by 50.1 gallons/ hour (output) = 1.25 hours (or 75 minutes) of irrigation time @ 10 psi. This application of water should be divided between two to three equally long irrigation sets each week, 40 or 25 minutes in length respectively.
- 20% more time should be added to compensate for evaporative losses, leakage, etc. These respective times should be increased to two 45-minute sets or three 30- minute sets/week.

Hands-On Exercises 4: Calculating a Water Budget for a One-Acre Block of Vegetables Using Sprinkler Irrigation

for the student

In the following exercise you will calculate the amount of irrigation time and frequency of irrigations required to replace the amount of water lost through evapotranspiration in your area from a one-acre block of vegetables using sprinkler irrigation.

EXERCISE 4

A. NUMBER OF GALLONS LOST THROUGH EVAPOTRANSPIRATION (ET) IN A ONE-ACRE FIELD:

- Step 1: Daily average summer evapotranspiration rate (ET) for an actively growing crop in full canopy in your area = ______ inches/day
- Step 2: Multiply this by 7 days/week = ______ inches/week

  Given: There are 27,158 gallons of water in an acre inch (the amount of water needed to cover an acre to a 1-inch depth)

  Given: An acre = 43,560 square feet (roughly 208 feet x 208 feet)

- Step 3: Multiplying ______ inches/week (ET) x 27,158 gallons/acre inch = ______ gallons/acre of water lost each week through evapotranspiration in an actively growing crop in full canopy in your area.

B. SPRINKLER IRRIGATION OUTPUT CALCULATIONS

- Step 4: Flow rate in gallons per minute (gpm) from an individual sprinkler head ______
- Step 5: Given: There are roughly 109 sprinkler heads per acre using 20 foot pipes set 20 feet apart. (20 feet x 20 feet = 400 square feet. 43,560 square feet/acre divided by 400 = 109)
- Step 6: 109 sprinkler heads x ______ gallons/minute each = ______ gallons per minute
- Step 7: _______ gallons/minute x 60 minutes/hour = ________ gallons/hour/acre total

C. CALCULATING IRRIGATION REQUIREMENTS

- To calculate the amount of irrigation time required (in hours/week) to replace the amount of water lost through evapotranspiration each week, complete the following calculations:
- Divide the total in Step 3 ______ gallons/acre ET by the total in Step 7 ______ gallons/hour/acre from the irrigation system = ______ hours of irrigation time required each week. This total time should be divided in to 2–3 irrigation sets for mixed vegetable operations.

* Note: It is also important to factor in an additional 10–20% for evaporative losses due to extreme heat and wind conditions. It is further advisable to use several rain gauges to check the actual amount applied and to assess uniformity of application.

Hands-On Exercises 5 & 6: Sample Calculations—How Much Water Do I Need? How Many Acres Can I Irrigate?

for the student

OVERVIEW

In the following exercises you will calculate the total rate and volume of irrigation water that must be delivered to support two hypothetical farming operations. This information will help you determine the irrigation system needed to support the delivery of this volume of water.

EXERCISE 5: HOW MUCH WATER DO I NEED?

- I have 10 acres that I want to farm. The climate is Mediterranean with a fairly dry summer season. There is no well or pump on the property. The property is situated over an aquifer that has an adequate water supply. I have adequate capital to invest in a well and pump to supply irrigation water for my farm. I need to decide how much water I need (flow rate in gallons per minute) to irrigate the entire 10 acres, so that I can have the proper-sized well and pump installed.

GIVEN:

- At any time during the summer the entire 10 acres may be in production
- The daily average evapotranspiration rate (ET) during the summer months is about 0.30 inch per day
- There are 27,158 gallons of water in an acre inch
- You only plan to run the pump 12 hours per day
- There are 10,080 minutes per week (60 minutes/hour x 24 hours/day x 7 days/week)
- There are 5,040 minutes per week at 12 hours per day (10,080 divided by 2)

SOLUTION

1. Multiply 0.30 inches (ET) by 7 (days per week) to get 2.1 inches per week
2. Assume that your application will be 75% efficient and multiply 2.1 (inches per week) by 1.25 to get 2.625 inches per week (application rate to supply actively growing crops with adequate moisture for maximum yield during summer months)
3. Multiply 2.625 inches per week by 27,158 (gallons per acre inch) to get 71,290 gallons per acre per week
4. Multiply 71,290 (gallons per week) by 10 (acres) to get 712,900 gallons per week
5. Divide 712,900 (gallons per week) by 5,040 (minutes per week at 12 hours per day) to get 141.44 gallons per minute

   Your pump and well will have to deliver 141.44 gallons of water per minute to keep your 10-acre farm productive during the summer months. If you were willing to irrigate 24 hours per day you would only need an output of 70 GPM (gallons per minute).

EXERCISE 6: HOW MANY ACRES CAN I IRRIGATE?

Someone has just offered you 10 acres of farmland in the Pajaro Valley on the central coast of California. There is a pump and well on the property capable of delivering 15 GPM. There are no other sources of water in the area. Your daily average ET in the summer is 0.20 inch. How many acres of irrigated vegetables can you plant during the summer months without running short of water?

GIVEN

- The daily average ET during the summer months is about 0.20 inch per day
- There are 27,158 gallons of water in an acre inch
- The pump flow rate is 15 gallons per minute
- You are only able to run the irrigation 12 hours per day during peak use

SOLUTION

1. Multiply 15 gallons per minute (GPM) by 60 (min per hr) to get 900 gallons per hour
2. Multiply 900 gallons per hour by 84 (hours per week @ 12 hours per day) to get 75,600 gallons per week maximum pump output
3. If your average ET during the summer months is .20 inches per day for an actively growing crop in full canopy, then multiply .20 (daily ET) by 7 (days per week) to get 1.4 inches per week
4. Multiply 1.4 (inches per week ET) by 27,158 (gallons per acre inch) to get 38,021 gallons per acre per week to keep your full canopy crops supplied with adequate water during the summer months
5. Assuming your application efficiency is 75%, multiply 38,021 by 1.25 to get 47,526 gallons per week
6. Divide 75,600 (maximum pump output per week) by 47,526 (weekly crop need per acre) to get 1.6 acres

Your 15 GPM well is capable of irrigating 1.6 acres of actively growing crop in full canopy during the summer months assuming 75% application efficiency and with application happening 12 hours per day. If you are will-ing to irrigate 24 hours per day then you can irrigate 3.2 acres.

If you increase your efficiency by only using overhead during the night, and utilize drip tape, you could in-crease your crop area slightly. If you plant crops with a low moisture requirement and if your soil and climate are conducive to dry farming (deep clay soil, mild summer temperatures, and at least 30 inches of precipitation annually during the winter) you might be able to farm the entire 10 acres.

Assessment Questions

1) Describe four functions of water in an agricultural system.

2) What is soil saturation?

3) What is field capacity?

4) What is the level of soil moisture at which most crop plants require additional water?

5) Describe two ways that agriculturists determine the need for irrigation.

6) Number the following stages of crop development in terms of their sensitivity to drought/water stress (1 being most sensitive and 4 being least sensitive):

_____ Flowering

_____ Yield formation/fruit set

_____ Early vegetative growth

_____ Fruit ripening

7) The soil water condition between field capacity (FC) and permanent wilting point (PWP) is referred to as:

Assessment Questions Key

1) Describe four functions of water in an agroecosystem.
   - *plant support/turgidity*
   - *nutrient transport (soil solution)*
   - *plant cooling through transpiration*
   - *plant nutrient (photosynthesis)*
   - *soil moisture for soil organisms*

2) What is soil saturation?

   When water is filling all the available pore spaces in a given soil

3) What is field capacity?

   A soil is at field capacity when the free water/gravitational water drains from a saturated soil

4) What is the level of soil moisture at which most crop plants require additional water?

   50% of field capacity

5) Describe two ways that agriculturists determine the need for irrigation.
   - *Qualitative: Measuring for relative percentages of field capacity in the root zone of the crop*
   - *Quantitative: Determining the evapotranspiration rate of a given site and systematically replacing the amount of water lost each week through calibrated water delivery systems*

6) Number the following stages of crop developmental in terms of their sensitivity to drought/water stress (1 being most sensitive and 4 being least sensitive):

   1. Flowering

   2. Yield formation/fruit set

   3. Early vegetative growth

   4. Fruit ripening

7) The soil water condition between field capacity (FC) and permanent wilting point (PWP) is referred to as:

   Plant available water (PAW)

Resources

PRINT RESOURCES

TECHNICAL RESOURCES

Cleveland, David A. and Daniela Soleri. 1991. *Food from Dryland Gardens: An Ecological and Social Approach to Small-Scale Household Food Production.* Tucson, AZ: Center for People, Food and the Environment.

An overview of small-scale and community-based food production techniques intended for use by development educators and rural organizers in less developed nations. Encourages the development of gardens that serve local needs, that are based on local knowledge, and that conserve natural resources and the biodiversity of traditional crops. Includes an excellent section on the principles and practices of low-technology garden-scale irrigation.

Hanson, Blaine. 2009. *Measuring Irrigation Flow Rates*. Publication 21644. UC Irrigation Program, UC Davis. Oakland, CA: University of California Division of Agriculture and Natural Resources.

Provides growers and irrigation professionals with information about devices typically used to measure flow rates on farms. Includes descriptions of the various flow meters, their installation and operation, and the calculations for determining flow rates and amounts of applied water.

Hanson, Blaine, Larry Schwankl, and Allen Fulton. 2004. *Scheduling Irrigations: When and How Much Water to Apply.* Publication 3396. UC Irrigation Program, UC Davis. Oakland, CA: University of California Division of Agriculture and Natural Resources.

A technical reference for irrigation tools and techniques used in production agriculture. Includes many common calculations used to determine when to irrigate and how much water to apply.

Hanson, Blaine, Larry Schwankl, Steve Orloff, and Blake Sanden. 2011. *Sprinkle Irrigation of Row and Field Crops*. Publication 3527. Oakland, CA: Division of Agriculture and Natural Resources.

Provides practical information on the design, management, and maintenance of the sprinkle irrigation methods commonly used in California for irrigating field and row crops. Discusses energy and management considerations such as when to irrigate, how much water to apply, and how to monitor soil moisture, offers design considerations and troubleshooting ideas, and provides an overview of system uniformity and efficiency.

Hanson, Blaine, Larry Schwankl, and Terry Prichard. 1999. *Micro-irrigation of Trees and Vines*. Publication 94-01. UC Irrigation Program, UC Davis. Oakland, CA: Division of Agriculture and Natural Resources.

Offers an overview of the rationale for micro-irrigation and how to assemble, operate, and maintain such a system.

Hanson Blaine, Steve Orloff, and Blake Sanden. 2007. *Monitoring Soil Moisture for Irrigation Water Management*. Publication 21635. UC Irrigation Program, UC Davis. University of California, Agriculture and Natural Resources: Oakland, California.

Describes techniques for monitoring soil moisture as an alternate method to water-based balance methods of managing irrigation water. Using this method you can "see" what is going on in the soil and determine answers to some key irrigation management questions.

Schwankl, Larry, Blaine Hanson, and Terry Prichard. 2008. *Maintaining Micro Irrigation Systems*. Publication 21637. UC Irrigation Program, UC Davis. Oakland, CA: University of California Division of Agriculture and Natural Resources.

Discusses the maintenance issues of microirrigation systems that can be used on tree crops, row crops, and trees and vines.

RESOURCES ON WATER ISSUES

California Roundtable on Water and Food Supply. 2011. *Agricultural Water Stewardship: Recommendations to Optimize Outcomes for Specialty Crop Growers and the Public in California, June 2011.* Ag Innovations Network.

California Roundtable on Water and Food Supply. 2014. *From Crisis to Connectivity: Renewed Thinking about Managing California's Water and Food Supply, April 2014.* Ag Innovations Network.

Roundtable members identified agricultural water stewardship as a key area of importance for sound long-term water management. The group held a series of meetings to build a common understanding of agricultural water use, develop a unified set of principles that underlie long-term solutions, and create recommendations for decision-makers and the public on balanced solutions to tough agricultural water issues. These reports are the product of those efforts.

Carle, David. 2009. *Introduction to Water in California.* California Natural History Guides No. 76. Berkeley, CA: University of California Press.

Describes the journey of California's water, from snowpack to field and faucet. Discusses the role of water in agriculture, the environment, and politics, and includes an update on recent water issues facing the state.

Donahue, John M., and Barbara Rose Johnston. 1997. *Water, Culture, and Power: Local Struggles in a Global Context.* Washington, DC: Island Press.

Presents a series of case studies from around the world that examine the complex culture and power dimensions of water resources and water resource management.

Mount, Jeffrey F. 1995. *California Rivers and Streams: The Conflict between Fluvial Process and Land Use.* Berkeley, CA: University of California Press.

Provides an overview of processes shaping California's rivers and watersheds, and the impact on water-ways of different land use practices, including agriculture.

Pielou, E. C. 1998. *Fresh Water.* Chicago, IL: University of Chicago Press.

A natural history of fresh water that includes an explanation of the dynamics of the water cycle and groundwater.

WEB-BASED RESOURCES

Appropriate Technology Transfer for Rural Areas (ATTRA) – Drought Resource Guide

attra.ncat.org/downloads/drought_RL.html

Provides a list of journals and websites with information on general farm management practices that can help mitigate the impacts of drought conditions. Accompanies ATTRA Powerpoint presentations on drought.

California Agricultural Water Stewardship Initiative

agwaterstewards.org

The California Agricultural Water Stewardship Initiative (CAWSI) works to raise awareness about approaches to agricultural water management that support the viability of agriculture, conserve water, and protect ecological integrity in California. A project of the Community Alliance of Family Farmers, CAWSI's website includes a resource library, case studies, information on on-farm practices, an events calendar, and other resources.

California Irrigation Management Information Systems (CIMIS)

www.cimis.water.ca.gov

California weather information site designed to help growers, turf managers, and others properly time irrigation applications.

Drought Proofing Your Farm Checklist

aginnovations.org/agwaterstewards.org/uploads/docs/Cahn-drought_proofing_checklist.pdf

Based on a presentation at the 2010 Ecological Farming Conference in Asilomar, CA by Michael Cahn, Cooperative Education irrigation and water resources advisor for Monterey County. Outlines general strategies and specific steps to take in drought proofing your farm.

Effective Irrigation Practices To Improve Short Term and Long Term Water Management

ftp://ftp-fc.sc.egov.usda.gov/CA/news/Publications/factsheets/effective_irrigation_practices.pdf

Provides step-by-step guidelines to maximize distribution uniformity, minimize evaporation losses, and optimize water application timing and amount decisions for a variety of irrigation systems, including furrow irrigation, hand-moved and solid set sprinklers, microirrigation, and drip irrigation.

Estimating Soil Moisture by Feel and Appearance. USDA NRCS Program Aid Number 1619

www.nrcs.usda.gov/wps/portal/nrcs/detail/mt/newsroom/?cid=nrcs144p2_056492

PDF available at: www.ext.colostate.edu/sam/moisture.pdf

This user-friendly guide describes how to use the "feel and appearance" method to estimate soil moisture. Includes photos of a range of soils at various moisture levels and provides useful guidelines for estimating soil moisture conditions, e.g., by using the "squeeze test."

Irrigation Scheduling: The Water Balance Approach.

www.ext.colostate.edu/pubs/crops/04707.html

Describes the water balance approach to irrigation scheduling.

Measuring and Conserving Irrigation Water

attra.ncat.org/attra-pub/summaries/summary.php?pub=332

Describes how to find the net water application rate for any irrigation system. Explains how to calculate the number of hours the system should be operated, describes several ways to measure flowing water in an open channel or pipeline, and offers suggestions for irrigating with limited water supplies.

Methods of Determining When To Irrigate. Cooperative Extension, College of Agriculture and Life Sciences, The University of Arizona.

cals.arizona.edu/pubs/water/az1220/

Details a variety of techniques used to determine irrigation scheduling, including the "feel method," tensiometers and other soil moisture measuring devices, infrared thermometers that measure the temperature of the plant canopy, and computerized irrigation models.

UC Davis Small Farm Center, Family Farm Series Publications: Vegetable Crop Production—Tips on Irrigating Vegetables

www.sfc.ucdavis.edu/Pubs/Family_Farm_Series/Veg/vegcrop.html

Information on pre-irrigation, timing, irrigation system options, and other useful tips for irrigating vegetable row crops.

UC Division of Agriculture and Natural Resources: Institute for Water Resources, Water and Drought Online Seminar Series

ciwr.ucanr.edu/California_Drought_Expertise/Insights__Water_and_Drought_Online_Seminar_Series/

This online seminar series from the University of California, Agriculture and Natural Resources, developed with support from the California Department of Water Resources, brings timely, relevant expertise on water and drought from around the UC system and beyond directly to interested communities. Topics include using agroecological practices to enhance the resilience of organic farms to drought, vineyard irrigation with limited water, saving water in the landscape, and much more.

UC Division of Agriculture and Natural Resources: Irrigation

www.anrcatalog.ucdavis.edu

Publications and instructional materials on irrigation.

The WATER Institute

www.oaecwater.org

The WATER Institute (Watershed Advocacy, Training, Education, & Research), based at the Occidental Arts and Ecology Center in Occidental, California, promotes understanding of the importance of healthy watersheds to healthy communities. The Institute's website offers numerous resources and links to important readings about water politics, conservation, traditional practices, and water history.

SUPPLEMENT 1

Evapotranspiration (ET) & Factors that Affect ET Rates

Many factors affect ET, including weather parameters such as solar radiation, air temperature, relative humidity, and wind speed; soil factors such as soil texture, structure, density, and chemistry; and plant factors such as plant type, root depth, foliar density, height, and stage of growth.

Evapotranspiration (ET) = Evaporation + Transpiration

Evaporation is the transformation of water from a liquid into a gas. Water volatilizes into the air easily, especially when it is hot and windy. Evaporation happens only at the surface of a liquid, so the greater the surface area-to-volume ratio of the water, the greater the evaporation rate. This means that you lose more water to evaporation from water sprayed in drops into the air than you do from water in a drip tape line or in an irrigation canal or ditch.

The evaporation rate (i.e., the time it takes for a certain amount of water to volatilize) for a given day can be measured. One way is by placing a known quantity of water in a container of a known surface area and timing how long it takes to disappear. In California, we can also look up this value on a state-run website indexed by geographical area, the California Irrigation Management Information System website, *www.cimis.water.ca.gov.*

Transpiration is the transformation and use of water by a plant. The plant uses water to transport nutrients and air, to maintain its structure, and to thermoregulate (maintain optimal temperature). The transpiration rate of a plant is the amount of water a plant uses up over a given amount of time. This value is harder to measure, as it is difficult to assess the minimum amount of water that a plant needs to be healthy. The plant could be using less water than you are giving it. You could measure this in a very controlled environment by giving similar plants different amounts of water and seeing the effects. Fortunately, this can also be looked up. Transpiration rates found in reference tables are generally for mature plants; any plants that are working more (flowering, setting fruit, at a critical stage of growth, etc.) will transpire more. It is equivalent to breathing for us – adults use more air than children do, you use more when you are exerting yourself, etc.

Evapotranspiration or **ET** is the combined use of water by plants and loss of water into the air (see Appendix 1: Soil Moisture Terms, for an illustration). The evapotranspiration rate is the amount of water that needs to be replaced over a given amount of time to make up for the water that has been used or volatilized. The evapotranspiration rate is measured for mature plants in a given region on a given day.

Precipitation and irrigation are the two primary sources of water that plants use. Plant leaves and soil surfaces temporarily retain some part of the water applied to the field, but this part readily evaporates. What remains percolates into the soil. Plants extract the infiltrated water through their roots and transport it up to their leaves for photosynthesis. In addition to water, plants need carbon dioxide (CO_2) and light for photosynthesis. In order to take in CO_2 from the atmosphere, plants open their stomata, the microscopic pores on the undersides of leaves. It is during this process that they lose water to the atmosphere.

Some Environmental Factors Affecting the Rate of Transpiration

LIGHT

Plants transpire more rapidly in the light than in the dark. This is largely because light stimulates the opening of the stomata. Light also speeds up transpiration by warming the leaf.

TEMPERATURE

Plants transpire more rapidly at higher temperatures because water evaporates more rapidly as the temperature rises. At 86°F, a leaf may transpire three times as fast as it does at 68°F.

HUMIDITY

When the surrounding air is dry, diffusion of water out of the leaf happens more rapidly.

WIND

When there is no breeze, the air surrounding a leaf becomes increasingly humid thus reducing the rate of transpiration. When a breeze is present, the humid air is carried away and replaced by drier air.

SOIL WATER

A plant can continue to transpire rapidly if its water loss is made up by replacement water from the soil. When absorption of water by the roots fails to keep up with the rate of transpiration, loss of turgor (rigidity caused by pressure of water against cell walls) occurs and the stomata close. This immediately reduces the rate of transpiration (as well as of photosynthesis). If the loss of turgor extends to the rest of the leaf and stem, the plant wilts.

The volume of water lost in transpiration can be very high. It has been estimated that over the growing season, one acre of corn plants may transpire 400,000 gallons of water. As liquid water, this would cover the field with a lake 15 inches deep.

SUPPLEMENT 2

Overview of the "Water Budget Approach" to Irrigation Management

Water budgets are analogous to maintaining a balanced checkbook. Additions of irrigation water or rainwater are "deposits" and water use by plants as well as evaporation from the soil surface are "withdrawals." The starting point for a water budget is a soil saturated from either irrigation or rainfall. From that initial point of saturation, water depletion is monitored and water is applied as needed to maintain a "balanced" system to optimize plant growth.

This "quantitative" water budget approach to irrigation scheduling has been used successfully by large-scale farming operations in arid regions of the western United States since the early 1980s. Through a network of regional weather stations, daily weather data including reference ETo is made available to growers in many agricultural regions throughout the west. Weather information from these stations is commonly used by large-scale irrigation managers and research plot managers to assist in accurately determining how much water to apply to crops in order to avoid over application of irrigation water, while at the same time maximizing crop yields of agronomic, orchard and vegetable crops. Though this system of irrigation scheduling is simply not practical or appropriate for diverse small-scale agricultural systems, many of the principles are applicable and can be effectively used by irrigation managers of smaller scale systems as a means of increasing overall irrigation efficiency on their farms and in their gardens.

From an irrigation standpoint the most important data from this network of weather stations is what is referred to as "reference crop evapotranspiration" (ETo). The ETo is the estimated daily rate of evapotranspiration from a reference crop, which is either grass or alfalfa in full canopy. In most locations these data are given in "inches per day." With these data a grower can calculate "crop evapotranspiration"(ETc) and determine how much water to apply to an actively growing crop.

The other critical piece of information needed for the irrigation rate calculation is the "crop coefficient"(Kc). The crop coefficient reflects the stage of growth of the crop from seedling through full canopy. Crop Coefficient (Kc) information is available for a limited number of economically important crops typically produced in large-scale systems. For this reason this system of irrigation management is typically not used in small-scale diverse systems. In its simplest terms the crop evapotranspiration rate (ETc) equals the crop coefficient (Kc) multiplied by the reference crop evapotranspiration rate (ETo).

ETc = Kc x ETo

Using corn as an example:

- A corn crop at 10 days from emergence would have an estimated Kc value of .25
- A corn crop at 45 days from emergence would have an estimated Kc value of .50
- A corn crop at 100 days from emergence would have an estimated Kc value of 1.00

If the corn crop had been irrigated at time of planting and the daily ETo averaged .15 inches per day for the first ten days since emergence, then your irrigation calculation for day ten would be as follows:

ETc = .25 (Kc) x 1.5 (.15" ETo per day X 10 days)

ETc = .375 inches

Based on this equation would you irrigate the corn with .375 inches of water on day ten?

You might be better off accessing soil moisture using a shovel and the "feel" method at this growth stage. The Kc is not an absolute number but only an estimate since it would change on a daily basis from emergence of the crop through to maturation. What is most important to understand from this example is that most vegetable crops, when in full canopy, have a Kc value of 1. If we can get an accurate estimation, from a local weather station, of the average ETo rate then we can easily determine an approximate weekly rate of irrigation for most crops —when in full canopy—typically grown in small-scale diverse systems.

For example if our average ETo is about .15 inches per day then we would need to apply roughly 1 inch per week of irrigation water to a crop in full canopy.

ETo .15″ per day times 7 days per week = 1.05″

There are many other considerations to take into account when making irrigation decisions, including soil type, crop type, time of harvest, and irrigation system application uniformity, but the "water budget" method of irrigation rate calculation does, when used properly, provide a basis for sound decision making in small-scale farms and garden—especially when used in conjunction with the "feel" method.

SUPPLEMENT 3

Soil Moisture Sensing Instruments Commonly Used for Irrigation Scheduling

Information from soil moisture sensing instruments can help inform decisions about when and how much to irrigate vegetable, vine, and tree crops. Although these instruments can't replace the knowledge and experience gained from both qualitative ("by feel") and quantitative approaches to measuring soil moisture discussed elsewhere in this unit, they can be used in tandem with these methods to help determine crops' needs.

There are a number of soil moisture sensors available to growers, but two general categories have come to be industry standards because of their relative low cost, accuracy, reliability, and ease of use. Currently, tensiometers and electrical resistance sensing devices (ERSDs) are the instruments most commonly used in California's Central Coast region.

Tensiometers

In simple terms, a tensiometer is a tightly sealed plastic water-filled tube with a semi-porous ceramic tip at the bottom, which is buried in the soil. A vacuum gauge near the top of the tube (above grade) provides constant readings that reflect soil moisture conditions at the depth of the ceramic tip.

Starting from a point of field capacity, as plant roots extract available water from the soil, water is pulled from the sealed tensiometer tube into the surrounding soil. This "pull" or "tension" is measured in centibars on the vacuum gauge attached to the tensiometer. The dryer the soil becomes, due to plant extraction of irrigation water, the higher the centibar readings; thus a reading of 0 reflects saturation and a reading of 100 reflects very dry soil. Irrigation is often required at readings between 30 and 50 centibars, although this can vary considerably depending on crop, soil type, and climate.

Placement

Tensiometers are placed directly into the most active part of the crop's root zone, at depths ranging from 6 inches to as deep as 48 inches. The most common placement depths are 6 and 12 inches for shallow-rooted crops (e.g., strawberries).

Two tensiometers are often placed next to each other so that soil moisture can be monitored at different depths at the same location. The deeper location tends to maintain a higher percentage of moisture compared to the more shallow placement, and this difference provides the irrigator with a good representation of below-ground moisture dynamics that can be a great help in determining both timing and amounts of water needed to meet the crop's needs over time.

Tensiometers should be placed at a number of locations across the field to reflect different soil and irrigation conditions. They should be left in place for the duration of the crop cycle and read as often as once a day to inform irrigation scheduling decisions.

Placement location and method of installation are critical for accuracy. Tensiometers should be placed within the root zone directly in the "wetted" area that receives either drip or sprinkler irrigation. In sprinkler-irrigated systems, place the tensiometers between sprinkler risers where maximum uniformity is often observed. In drip-irrigated systems, place the tensiometers off to the side of the drip line but still within the wetting pattern of the drip.

Prior to placing the tensiometer in the soil the semi-porous ceramic tip must be soaked in water overnight to insure that it is adequately moist so that water can easily move from the sealed tube into the surrounding soil.

To install the tensiometer the irrigator makes a hole in the ground to the desired depth and the same diameter as the tensiometer. There are dedicated tools for this purpose, but a soil probe can be used as long as it is the same diameter as the tensiometer. A slurry of soil and water is poured into the bottom of the hole to ensure good tensiometer-soil contact (critical for accurate readings), and the tensiometer is then pushed into place in the hole. The tensiometer location should be marked with a flag to facilitate locating the instruments for monitoring. Once installed it usually takes several readings over a period of several days to start getting accurate readings.

Tensiometers have a water reservoir above the sealed column of water that resupplies the plastic column, since the plant roots constantly extract very small quantities of water from the sealed tube. To refill the sealed tube the irrigator simply unscrews the cap on the reservoir and this opens the seal below the reservoir, allowing the excess water in the reservoir to flow into the lower tube. Once the tube is filled, a small hand-held suction pump is used to remove air bubbles from the tube. The lid of the reservoir is then retightened, sealing the lower tube. It is important to follow all of the manufacturer's recommendations for installation and maintenance, including the use of an additive to minimize algal contamination of the water in the tensiometer.

When used properly, tensiometers will provide accurate "soil/water tension" readings on a range of crops. These readings provide the irrigation manager with critical information that can be used to establish irrigation schedules adequate to maintain soil moisture at levels conducive to good crop growth and productivity.

Electrical Resistance Sensing Devices

In many ways electrical resistance sensing devices (ERSDs) are similar to tensiometers—the main difference is the method used to measure soil moisture. ERSDs utilize two "electrodes" cast into a porous material (often gypsum based). The two electrodes in the "block" are attached to wires that run from the ERSD to the surface. These wires are often protected within a ½-inch PVC tube that is attached to the ERSD. The ESRDs are buried in the soil at various depths and locations, similar to tensiometers, and like the tensiometer, a soil/water slurry is used when the ERSD is installed to establish good soil contact with the instrument.

To get a reading from the ERSD the irrigator uses a small, inexpensive, hand-held electrical resistance meter that is temporarily connected to the wire leads from the buried ERSD. The meter allows a very low electrical current to flow between the two electrodes in the ERSD and displays an electrical resistance reading. This reading reflects the amount of moisture within the porous material, since the buried ERSD takes on the moisture properties of the surrounding soil. Due to the electrical conductivity potential of water, the higher the concentration of moisture within the porous block the lower the resistance and, conversely, the lower the concentration of moisture within the block the higher the resistance.

At field capacity the block is wet; as the growing plants start to extract moisture from the soil, the moisture is also pulled from the ERSD and the conductivity reading will reflect this change in soil moisture. Note that high salt concentrations in the soil solution will affect the accuracy of the reading, since salts increase electrical conductivity. This potential salt impact needs to be taken into account when deciding which monitoring tool is best suited to your farm.

Electrical resistance sensing devices are relatively inexpensive and easy to install and monitor. Like tensiometers, they are left in the field for the duration of the cropping cycle and provide critical irrigation scheduling information that enables the irrigation manager to make informed decisions about irrigation frequency and quantity based on site-specific data.

SUPPLEMENT 4

Overview of Dry Farming on the Central California Coast

"Dry farming" is a term that growers and consumers on California's Central Coast use to describe summer- and fall-harvested orchard, vineyard, and vegetable crops grown without supplemental irrigation following planting. Rather than rely on irrigation, dry-farmed crops draw on a reserve of soil moisture "captured" by the grower following winter and early spring rains.

A limited number of geographic regions are suited to dry farming, which requires adequate winter rainfall and, in the case of annual crops, a summertime marine influence that generates cool mornings and warm afternoons. These conditions, combined with careful soil preparation, appropriate variety selection, adequate plant spacing, and vigilant weed control are all required for successful dry farming.

A Note About Dry Land Farming

"Dry land farming" is another term commonly used in agricultural production. The term typically refers to winter grain production on non-irrigated cropland. Dry land grain is planted in fall and harvested in spring/early summer, relying on winter rainfall for growth and development. A dry land grain crop usually requires between 10 and 15 inches of annual precipitation for economic yields. In areas where rainfall is less than 10 inches, with careful soil management, grain can be produced every other year.

The important distinction between dry farming and dry land grain production is that the grain crop is "rain irrigated" during most of its growth cycle. In contrast, dry-farmed crops experience little or no rainfall during the growth cycle of the crop. In this supplement we are specifically referring to "dry farming."

Criteria for Successful Dry Farming

MEDITERRANEAN CLIMATE

Central California's Mediterranean climate creates the conditions that make dry farming possible. In normal years Central Coast rainfall is generated by storms that develop in the Gulf of Alaska and sweep south and then east, moving from the Pacific Ocean across the region from November through February and into March. High pressure then dominates the region from April through September and often into October, pushing rainfall to the north during the Central Coast's long "summer drought." Thus the region rarely receives significant rainfall from May through September.

Rainfall amounts vary considerably across the Central Coast, influenced in large part by the location, height, and orientation of the area's numerous mountain ranges. Steeper ranges parallel to the coast can cause significant orographic (mountain-induced) lifting of moisture-laden air, resulting in high rainfall amounts on the west side of these slopes. These ranges also create rain shadows on the east (inland) sides, reducing rainfall in these areas. From San Luis Obispo County in the south to San Mateo County in the north, rainfall amounts vary from approximately 8 inches up to approximately 35 inches per year depending on the effects of the mountain ranges and specific storm dynamics.

ADEQUATE WINTER RAINFALL

A minimum of 20 inches of rainfall during the rainy season is required to create an adequate reserve of soil moisture for growing most dry-farmed crops. The challenge for the dry-farm grower is to capture and hold as much of this precipitation in the soil as possible so that the spring-planted dry-farmed crops can access this "stored" moisture during the dry summer months.

MARITIME INFLUENCE

The valleys along the coast in Central California that receive significant summer time marine influence in the form of early morning fog and mild afternoon high temperatures (highs in the mid 80°s) and evapotranspiration (ET) rates in the range of .15 inches per day are ideal for dry farm production.

Higher afternoon temperatures and ET rates in the range of .33 inches per day, typically encountered in the more inland valleys with less marine influence, are much less suited to dry farming, especially of tomatoes, since it can be difficult for the plants to access deeper moisture quickly enough to maintain turgidity during periods of high evapotranspiration. However, some crops can be successfully dry farmed in inland valleys: although not within the scope of this article, wine grapes, olives, and apricots are successfully dry farmed in California on small acreages in areas with little or no maritime influence.

SOIL TYPE

The best soils for dry farming have relatively high clay content. Sandy loam soils or loam soils that overlay deeper clay soils also work well for dry farming. Soils higher in sand content do not hold soil moisture as well as clay and clay loam soils and therefore are typically not used for dry farming. And because organic matter increases the soil's porosity, it does not improve conditions for dry farming.

A grower considering dry farming should bore numerous holes up to 4 feet deep throughout the production area using a 2-inch slide hammer and soil probe to obtain soil "plugs": soils suitable for dry farming will exhibit continuity within the different horizons and a loam or sandy loam upper horizon going directly to clay. Horizons with a larger particle size, e.g., containing sand or gravel, will impede water's ability to be drawn upward to the plant's root zone, thus making dry farming less feasible. Preparing and planting a small area of the field is the best way to determine whether the site and conditions are suited to dry farming.

Soil Preparation

Soil preparation that conserves or "traps" winter rainfall is critical for successful dry farming. In the spring, prior to planting, residual rain moisture is typically lost from the root zone as water percolates down through the soil horizon with the help of gravity. High clay content in the soil, and to a lesser extent soil organic matter (humus), greatly facilitates the soil's ability to hold water in the root zone against the pull of gravity.

As the weather warms, soil moisture is also lost through surface evaporation. Evaporation occurs as water is drawn upward via small channels between soil particles; these channels can be thought of as capillaries within the soil horizon. Polar bonds between water molecules and the forces of cohesion facilitate water's upward movement through the soil: as water near the soil surface evaporates, water lower in the soil is pulled nearer the surface, much like liquid being drawn through a straw. Thus in fields destined for dry farming it is critical to break up the capillaries near the surface to minimize the evaporative loss of residual rain moisture during late spring and summer.

This breaking of capillaries is typically accomplished with relatively shallow (8"–10") mechanical soil tillage. Commonly used tillage tools include rototillers and disc harrows, often followed by secondary tillage implements such as spring tooth harrows. The resultant tilled zone is called a "dust mulch." This dust mulch provides an effective barrier to the potential evaporative loss of residual rain moisture held within the root zone of the soon-to-be-planted dry-farmed crop.

When creating the initial dust mulch, timing is critical: the grower must trap as much rain moisture in the soil as possible, yet avoid working the soil when it is too wet. Wet soils, especially "heavier" soils high in clay content, are subject to clod formation and compaction caused by tractor operations.

It is also important to minimize tillage depth when preparing soil for planting annual dry-farmed crops, since deeper tillage could disrupt the lower soil capillaries that are critical for soil water movement below the tilled zone. The dust mulch needs to be maintained with fairly frequent and light tillage operations (every two or three weeks) from the time of initial tilling until the crops are too large to cultivate effectively.

Although dry farming relies on winter rainfall, several scenarios can necessitate irrigation prior to planting. During dry springs it is sometimes necessary to pre-irrigate the beds before planting using either overhead irrigation or drip lines in order to establish an optimal stand. When a mechanical spader is used to incorporate a high residue cover crop prior to dry farming it is often necessary, in the absence of post-tillage rain events, to pre-irrigate with overhead sprinklers to facilitate the cover crop's breakdown. On a garden scale, you may need to hand water the newly planted plants to assist in rooting and uniform establishment.

The typical springtime dry farm tillage and crop culture sequence at the UCSC Farm is as follows:

1. Flail mow cover crop
2. Incorporate cover crop residue with mechanical spader
3. Form beds with rolling cultivator
4. In the absence of rain, pre-irrigate beds with over head irrigation at a rate of 1.5 inches per acre (when spring rains are adequate this step is unnecessary)
5. Wait for weed flush and create dust mulch with rolling cultivator
6. Maintain dust mulch with rolling cultivator as needed until planting time
7. At time of planting break open bed middles with Alabama shovels and plant tomato transplants deeply into moisture using hand trowels
8. Cultivate with sweeps and side knives when first weeds appear in furrow bottoms or as necessary to maintain dust mulch
9. Once plants reach adequate height, reform beds by throwing dirt into bed middles with rolling cultivator—when timed well this last cultivation pass will also effectively smother weeds starting to establish within the plant line

Variety Selection

In any dry farming system, variety selection is absolutely critical. Varieties that do well as dry-farmed crops typically have an aggressive root system capable of reaching deep into the soil horizon to tap the stored rain moisture.

It is interesting to note that growers in the Central Coast region have trialed literally hundreds of varieties of heirloom, open pollinated and hybrid tomatoes and, to date, none have compared to 'Early Girl' in their ability to set roots deep and consistently produce a high yield of high quality, flavorful, and marketable fruits with no irrigation. 'New Girl', a recently introduced variety, is closely related to 'Early Girl' and appears to have many of the same favorable characteristics.

Plant Spacing and Weed Control

Dry-farmed crops with extensive root systems can effectively extract deep residual rain moisture from a fairly large area within their roots' grasp. Competition from other nearby crop plants or weeds can result in water-stressed plants that produce very little fruit and remain stunted. For this reason it is critical to plant out dry-farmed crops in a much wider spacing than is typically used for irrigated crops of the same type. Good weed management in a dry farm system is also critical, since most weeds have aggressive root systems capable of outcompeting most crop plants for both water and nutrients.

As an example of plant spacing, irrigated tomatoes are commonly spaced 2 feet apart within the row with rows spaced 4 feet apart, a density of roughly 5,400 plants per acre. A typical spacing for dry-farmed tomatoes (depending on soil type and rainfall amounts) would be 6 feet between rows and 6 feet between plants, for a total plant population of 1210 plants per acre. As you can see from this example a significant yield reduction can be expected from most dry-farmed crops simply based on per acre plant populations. A higher price premium for dry-farmed tomatoes will often make up for the yield loss related to wider spacing.

Crops Suitable for Dry Farming

Tomatoes are the most notable dry-farmed crop produced in the Central Coast region. Dry-farmed tomatoes are typically transplanted into the field from May through June. It is advantageous to plant the tomatoes as deep as possible into the residual rain moisture after the dust mulch has been created and when soil temperatures are adequate for strong growth (>55 °F). Growers often plant several successions spaced 2 to 3 weeks apart to provide an extended fall harvest period. Some growers stake and tie the tomatoes for ease of harvest and to enhance fruit quality, while others let the plants vine out on the ground without support.

'Early Girl' and/or 'New Girl' are currently the tomato varieties of choice. The fruits are easy to handle, they don't crack, and the flavor is remarkable. However, when grown without irrigation, these varieties are prone to a physiological condition known as blossom end rot. Blossom end rot is related to the plant's inability to move calcium to the blossom end of the fruit, which is exacerbated when water is limited. The symptom is a black sunken spot on the blossom end of the fruit that—depending on the severity of the symptom—is prone to rot. Although the condition often becomes less prevalent as the season progresses, it may affect 10–20% of the crop. Fruit showing symptoms of blossom end rot are not marketable.

Other annual vegetable crops that have been successfully dry farmed in the Central Coast region include dry corn, dry beans, and winter squash, all of which are direct seeded into residual rain moisture after the creation of the dust mulch. In a trial conducted at the UCSC Farm in the mid 1990s we showed no significant difference in yield between irrigated and dry-farmed Red Curry, Butternut, and Spaghetti winter squashes.

Advantages of Dry Farming

As a rotation within a diverse irrigated cropping system, dry farming has many advantages. The lack of irrigation in a dry-farmed production block can lead to improved soil tilth, since dry surface soil is not prone to compaction or clod formation from both foot traffic associated with harvest and tractor compaction from cultivation operations. Problem weeds are much easier to deal with when irrigation is eliminated for a season and weed seed development is easily minimized in a dry-farmed block. If water is a limited resource on a farm then dry farming makes perfect sense as a means of maintaining production while eliminating the need for irrigation. Forcing deep rooting of dry-farmed crops can also facilitate the extraction of nutrients that have leached below the root zone of most irrigated crops through excessive rainfall or irrigation.

Dry farming also heightens the intensity of crop flavors. This is particularly true of tomatoes, which are highly sought after by savvy consumers and the Central Coast region's chefs. As a result, the production and sale of dry-farmed tomatoes has become an important and economically viable niche market for small-scale organic specialty crop growers on the Central Coast.

Finally, although dry farming may not be appropriate for every cropping system and region, understanding the basic principles of dry farming can lead to a greater knowledge of the complexities of water and soil dynamics, tillage, weed management, and fertility management. This knowledge can in turn lead to a greater understanding of your particular production system. In regions where conserving water is critical, applying dry farming principles to irrigated systems can result in improved water use efficiencies, better weed management, and improved soil tilth and productivity.

SUPPLEMENT 5

Nitrate Contamination of Groundwater

Irrigation accounts for nearly one-third of all water use in the United States, or 128 billion gallons/day.[1] In arid western states, and California in particular, irrigation accounts for more than half of all water used. California uses about 24.4 billion gallons/day to irrigate some 9 million acres. This is about 6 times the amount of domestic water used by the entire U.S. population.[2]

While these statistics clearly illustrate the enormous quantity of water used in agriculture, they also suggest that irrigation has far-reaching consequences on water quality.

In an effort to maximize crop yields, many farmers apply nitrogen-based synthetic fertilizers. More than half of the nitrogen applied may go unused by crops, ending up in surface water runoff or leaching into groundwater and causing severe water quality and other public health concerns for rural communities, many populated by poor, immigrant farm workers.[3][4] As this supplement illustrates, how farmers use irrigation and apply fertilizers affects not only their crops, but also their neighbors.

Synthetic nitrogen-based fertilizers were made possible because of the Haber-Bosch process, which converts stable, inert nitrogen gas (N_2) unavailable to plants into the reactive ammonia molecule (NH_3) readily available for plant uptake. Once the process was commercialized, synthetic fertilizer use skyrocketed, as farmers were no longer dependent only on their soil organic matter, compost, cover crops, and livestock manure for nitrogen. Fertilizer use in the United States increased from about 7.5 million tons in 1960 to 21 million tons in 2010.[5] In 2007, California farmers applied 740,00 tons of nitrogen in fertilizers to 6.7 million acres of irrigated farmland.[6] With cheap sources of nitrogen and water available, our current agricultural system is based on the liberal application of synthetic fertilizers and irrigation water to ensure high yields, often at the expense of environmental and public health.

California's Central Valley is home to some of the most heavily fertilized cropland and some of the most polluted water in the United States. Communities there are particularly vulnerable to public health effects of nitrate contamination because groundwater provides drinking water for the majority of residents. Additionally, rural communities in the valley are generally poor and populated by immigrants and minorities least able to afford treatment costs and most vulnerable to discriminatory decision-making.

Tulare County, the second most productive agricultural county in California, includes many of these communities. Though it generates nearly $5 billion in revenue from agriculture each year, it has the highest poverty rate in California and is populated mainly by minorities (66%), most of whom

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4 Moore, Eli, and Eyal Matalon. 2011. The human costs of nitrate-contaminated drinking water in the San Joaquin Valley. Pacific Institute. *www.pacinst.org/wp-content/uploads/sites/21/2013/02/nitrate_contamination3.pdf*

5 USDA, Economic Research Service. Fertilizer use and price. Table 1: U.S. consumption of nitrogen, phosphate, and potash, 1960-2011. www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26720

6 Harter, Thomas. 2009. Agricultural impacts on groundwater nitrate. *Southwest Hydrology,* July/August 2009. *www.swhydro.arizona.edu/archive/V8_N4/feature2.pdf*

are Latino.[7 8 9] The average per capita income in the county is $18,021.[10] Here, one in five small public water systems and two in five private domestic wells surpass the maximum contaminant level (MCL) for nitrates.[11 12] As a result, residents of towns like Seville, East Orosi, and Tooleville are paying $60 per month for nitrate-contaminated water they can't safely use, and must spend an additional $60 to purchase bottled water for drinking and bathing. In contrast, San Francisco water customers pay $26 per month for pristine water from the Hetch Hetchy water system in Yosemite.

The economic cost of nitrate contamination in drinking water is not the only cost to these communities. Farm workers make up a significant segment of the population of small towns throughout the Central Valley and are both directly exposed to the hazards of heavy fertilizer use in the fields and in the air, and through excess nitrogen leached into groundwater drinking supplies. Scientists estimate that 50–80% of nitrogen applied in fertilizer is unused by plants. Of that, about 25% volatilizes into the atmosphere (some as nitrous oxide, the most potent greenhouse gas). As a result, approximately 30–50% of nitrogen applied in fertilizer—about 80 pounds per acre in California—leaches into groundwater beneath irrigated lands and into public and private water supplies.[13]

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8 USDA Economic Research Service. 2012. County-level data sets. *www.ers.usda.gov/data-products/county-level-data-sets/poverty.aspx#Pa8c98972d6c14aaea0543afd59db4088_3_382iT4*

9,10 United States Census Bureau. State and county QuickFacts, Tulare County. *quickfacts.census.gov/qfd/states/06/06107.html*

11 California State Water Resources Control Board. Groundwater ambient monitoring and assessment (GAMA). Domestic well project, groundwater quality data report, Tulare County focus area. Table 2: Summary of detections above drinking water standards. *www.swrcb.ca.gov/gama/docs/tularesummaryreport.pdf*

12 Brown, Patricia Leigh. 2012. The problem is clear: The water is filthy. *New York Times*, November 13, 2012. *www.nytimes.com/2012/11/14/us/tainted-water-in-california-farmworker-communities.html?pagewanted=all&_r=0*

13 Harter, Thomas. 2009. Agricultural impacts on groundwater nitrate. *Southwest Hydrology,* July/August 2009. *www.swhydro.arizona.edu/archive/V8_N4/feature2.pdf*

High nitrate levels in water can cause a number of health problems, including skin rashes, eye irritation, and hair loss. More severe is "Blue Baby Syndrome" (methemoglobinemia), a potentially fatal blood disorder in infants caused by consumption of nitrate-contaminated water. Direct ingestion, intake through juices from concentrate, and bottle-fed infant formula are all potential threats to children. Nitrate contamination has also been linked to thyroid cancer in women. Widespread contamination of groundwater through leached fertilizer has rendered drinking water in rural communities across the country not only unusable, but dangerously so.

While nitrate contamination is an acute problem in California, it exists across the country. The EPA estimates that over half of all community and domestic water wells have detectable levels of nitrates.[14] Rural communities that rely on private wells (which are unregulated), or lack access to adequate water treatment facilities, have the most insecure water supplies.

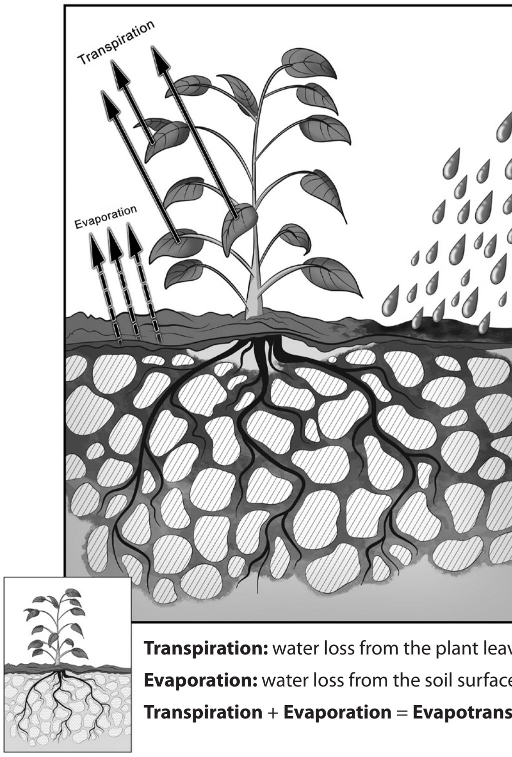
In the short term, municipalities must devise a plan to reduce the disproportionately high cost of water to these communities. One potential solution is a fee attached to the purchase of fertilizer used to subsidize water costs for communities with contaminated water. Communities with contaminated water could also be added to a nearby water district with access to clean water.

In the longer term, the obvious solution is to substantially reduce synthetic fertilizer and water use in agriculture. Treatment, while effective on a small scale, cannot keep up with the vast quantities of nitrates continually entering groundwater supplies through fertilizer application. Similarly, reduced irrigation on farms, drawn mostly from uncontaminated sources, frees up new sources of drinking water for nearby communities. Lastly, to reach a truly sustainable and equitable system of water distribution, residents of rural communities must be included in the planning and decision-making process as members of local water boards, irrigation districts, and planning commissions to establish and safeguard their right to uncontaminated water.

14 California State Water Resources Control Board. 2010. Groundwater information sheet. *www.waterboards.ca.gov/gama/docs/coc_nitrate.pdf*

Appendix 1: Water Cycling Terms

EVAPOTRANSPIRATION



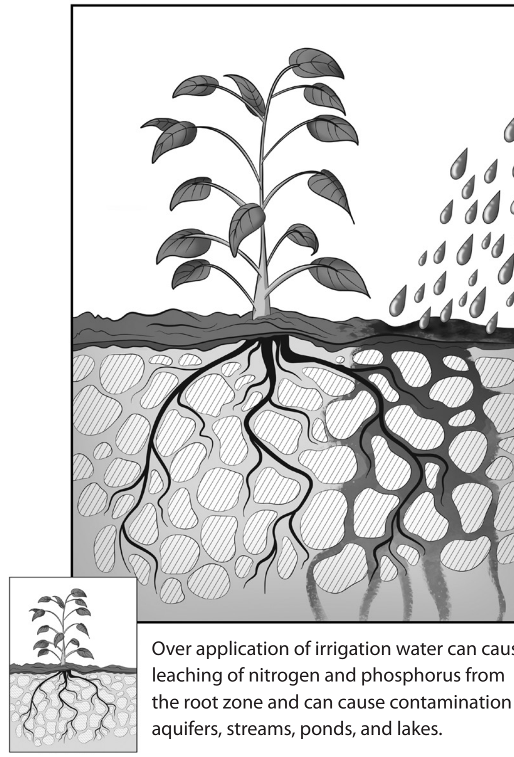
Initial state

Transpiration: water loss from the plant leaves

Evaporation: water loss from the soil surface

Transpiration + **Evaporation** = **Evapotranspiration (ET)**

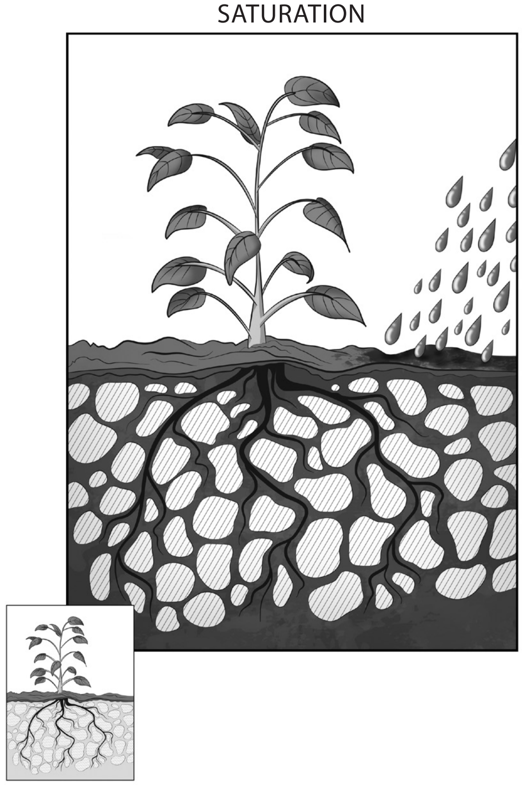
INFILTRATION / PERCOLATION



Initial state

Over application of irrigation water can cause leaching of nitrogen and phosphorus from the root zone and can cause contamination of aquifers, streams, ponds, and lakes.

SATURATION

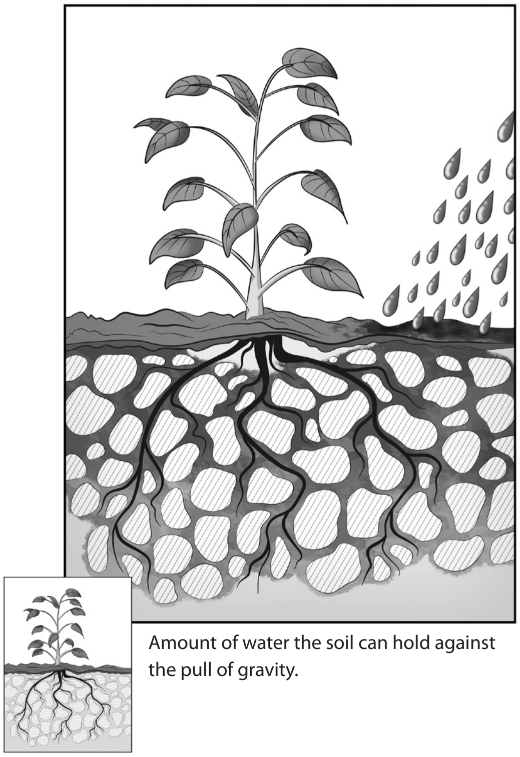


Initial state

Illustrations by José Miguel Mayo

Appendix 1 (cont.): Water Cycling Terms

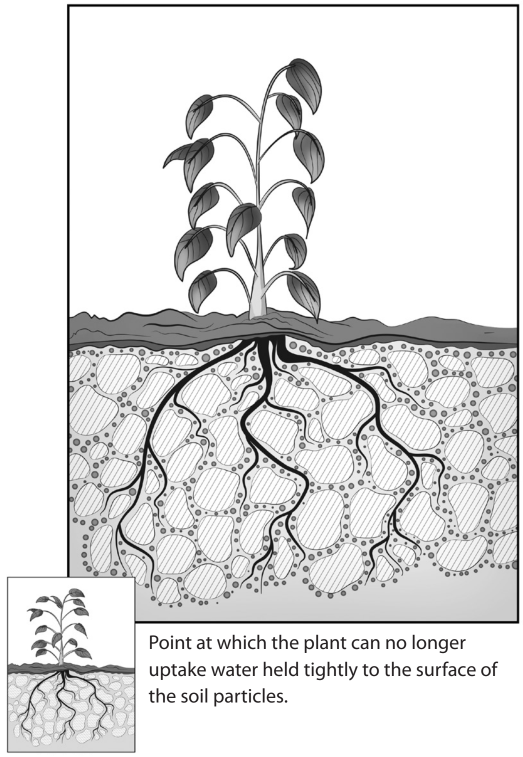
FIELD CAPACITY



Amount of water the soil can hold against the pull of gravity.

Initial state

PERMANENT WILTING POINT



Point at which the plant can no longer uptake water held tightly to the surface of the soil particles.

Initial state

Illustrations by José Miguel Mayo

Appendix 2: Units of Water Measurement

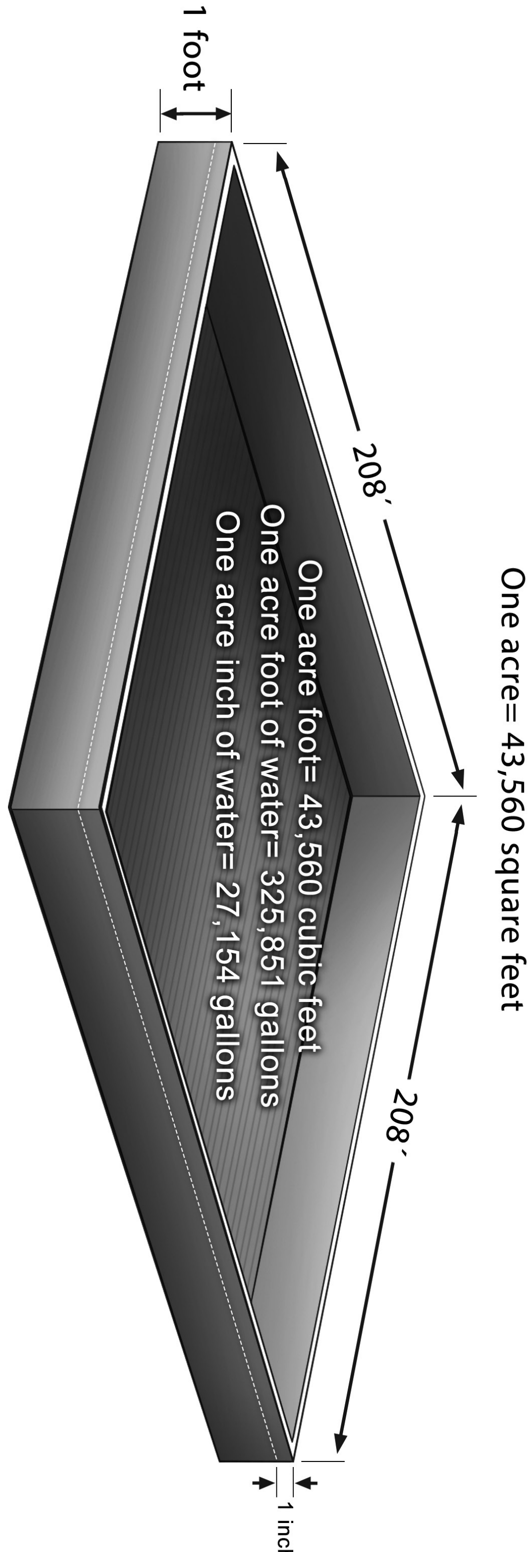


Illustration by José Miguel Mayo

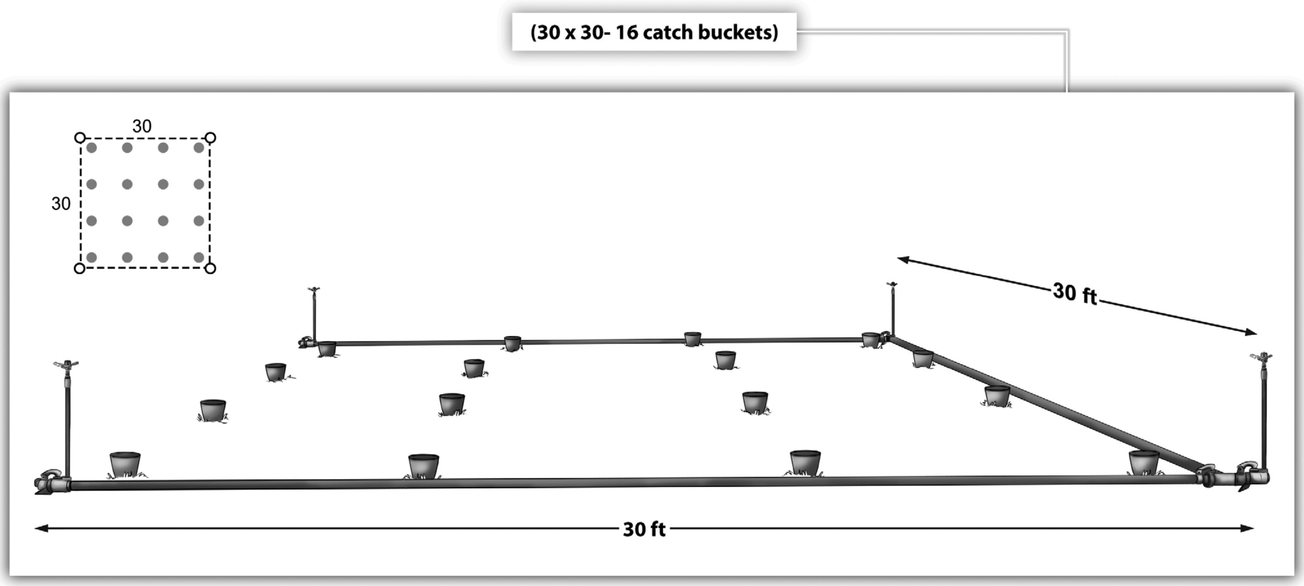
Appendix 3: Calculating Distribution Uniformity (DU)

Distribution uniformity (DU) is defined as how uniformly water is distributed over an area being irrigated, and is expressed as a percentage: the higher the percentage value, the more evenly water is distributed.

You can calculate distribution uniformity by collecting water in sample "catch buckets" or rain gauges laid out in an even grid between irrigation pipes or along the length of a drip line (see diagram). DU can then be determined using the "low quarter DU" method, in which the average of the lowest quarter of the samples collected is divided by the average of all samples to get a percent of distribution: 80% or above is considered an acceptable distribution uniformity.

SPRINKLER UNIFORMITY OF DISTRIBUTION TEST

(Uniformity based on average volume of lowest 25% of catch buckets divided by average of remaining 75%)



Head	Nozzle	psi	Rotation	Spacing	Duration	% Uniformity
Nelson rotator	7/64"	50	360	30 x 30	5 min	68.40%
Nelson rotator	7/64"	50	180	30 x 30	5 min	43.49%
Plastic impact	Blue	50	180	30 x 30	5 min	70.78%
Brass impact	1/8"	30	360	30 x 30	5 min	56.97%
Brass impact	1/8"	50	360	30 x 30	10 min	69.46%
Brass impact	1/8"	50	360	30 x 30	5 min	66.18%
Brass impact	1/8"	50	180	30 x 30	2.5 min	63.29%
Brass impact	1/8"	45	180	30 x 30	2.5 min	65.22%

Low quarter DU calculation: Average volume of lowest 25% of catch buckets divided by Average volume of all samples collected = Distribution Uniformity (DU)

Illustration by José Miguel Mayo

Appendix 3 (cont.): Calculating Distribution Uniformity (DU)

To calculate DU:

1. Lay out an evenly spaced grid of catch buckets or rain gauges between irrigation pipes or along a drip line (see diagram on page I-248); note that if you use the Taylor style rain gauges that measure precipitation/irrigation in inches, you can simultaneously test for application rate as well as uniformity
2. Run irrigation for 5 minutes
3. Measure and record the volume of water in each catch bucket or rain gauge
4. Rank the volume of water collected in each bucket or rain gauge, from lowest to highest
5. Calculate the average volume collected in the lowest 25% of catch buckets or rain gauges, and divide that number by the average volume of all the samples collected to get DU (measured as a percentage)

Example:
Average volume of lowest 25% of catch buckets = 4 inches
Average volume of all samples collected = 5 inches
DU = 4 divided by 5 = 80%

A low DU percentage (less than 80%) indicates poor distribution uniformity, i.e., one area of the field or bed is receiving significantly more irrigation water than other areas. Sources of poor uniformity can include malfunctioning or clogged sprinkler heads, differences in nozzle orifice sizes across a field, improper pipe spacing, improper operating pressure (too high or too low), windy conditions, and differences in pressure due to slope.

A similar DU test can be done for drip irrigation systems:

1. Once the system is brought up to pressure, collect water for a set amount of time (e.g., 5 minutes) in shallow containers placed beneath emitters, evenly spaced along drip lines at a number of locations in the field. Bury the trays to grade level so that they do not create undulations that might impact distribution uniformity
2. Make sure that all the containers are under the emitters for the same length of time
3. Measure and record the volume of water in each container
4. Use the "low quarter DU" method to calculate distribution uniformity. Note that using a number of containers/data points divisible by four will make the calculations easier.

Drip system uniformity can also be tested by taking pressure measurements using Shrader valves throughout the field. See a presentation of this method at:
www.agwaterquality.org/toms%20presentation%20DU%20in%20Drip%20and%20Sprinkler.pdf

Appendix 4: Estimating Soil Moisture by Feel

SOIL MOISTURE LEVEL (% OF FIELD CAPACITY)	COARSE (SAND)	LIGHT (LOAMY SAND, SANDY LOAM)	MEDIUM (FINE, SANDY LOAM, SILT LOAM)	HEAVY (CLAY LOAM, CLAY)
0–25% No available soil moisture. Plants wilt.	Dry, loose, single grained, flows through fingers. No stain or smear on fingers.	Dry, loose, clods easily crushed and will flow through fingers. No stain or smear on fingers.	Crumbly, dry, powdery, will barely maintain shape. Clods, breaks down easily. May leave slight smear or stain when worked with hands or fingers.	Hard, firm baked, cracked. Usually too stiff or tough to work or ribbon[1] by squeezing between thumb or forefinger. May leave slight smear or stain.
25–50% Moisture is available, but level is low.	Appears dry; will not retain shape when squeezed in hand.	Appears dry; may tend to make a cast[2] when squeezed in hand, but seldom will hold together.	May form a weak ball[2] under pressure but will still be crumbly. Color is pale with no obvious moisture.	Pliable, forms a ball; will ribbon but usually breaks or is crumbly. May leave slight stain or smear.
50–75% Moisture is available. Level is moderate to high.	Color is darkened with obvious moisture. Soil may stick together in very weak cast or ball.	Color is darkened with obvious moisture. Soil forms weak ball or cast under pressure. Slight finger stain, but no ribbon when squeezed between thumb and forefinger.	Color is darkened from obvious moisture. Forms a ball. Works easily, clods are soft with mellow feel. Will stain finger and have slick feel when squeezed.	Color is darkened with obvious moisture. Forms good ball. Ribbons easily, has slick feel. Leaves stain on fingers.
75% to field capacity (100%) Soil moisture level following an irrigation.	Appears and feels moist. Color is darkened. May form weak cast or ball. Will leave wet outline or slight smear on hand.	Appears and feels moist. Color is darkened. Forms cast or ball. Will not ribbon, but will show smear or stain and leave wet outline on hand.	Appears and feels moist. Color is darkened. Has a smooth, mellow feel. Forms ball and will ribbon when squeezed. Stains and smears. Leaves wet outline on hand.	Color is darkened. Appears moist; may feel sticky. Ribbons out easily, smears and stains hand, leaves wet outline. Forms good ball.

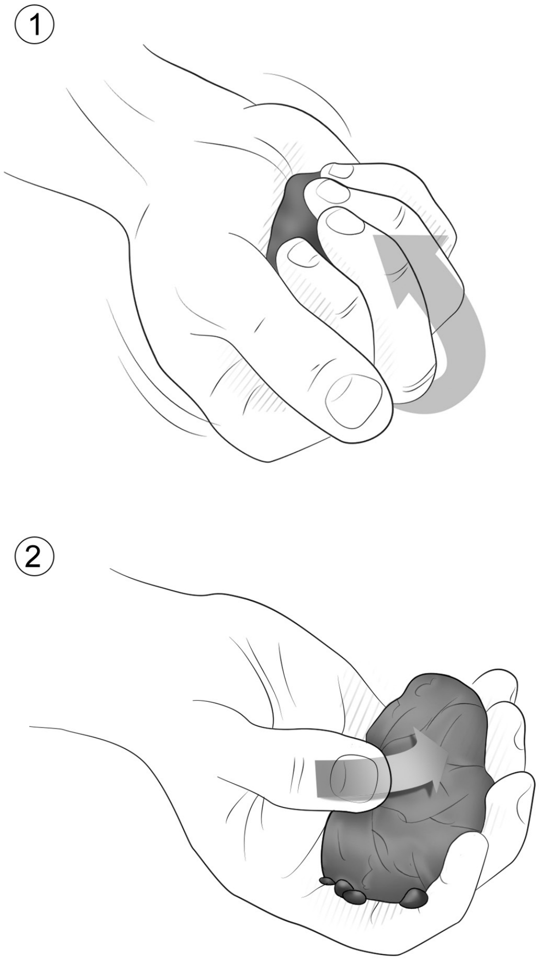
[1] Ribbon is formed by squeezing and working soil between thumb and forefinger

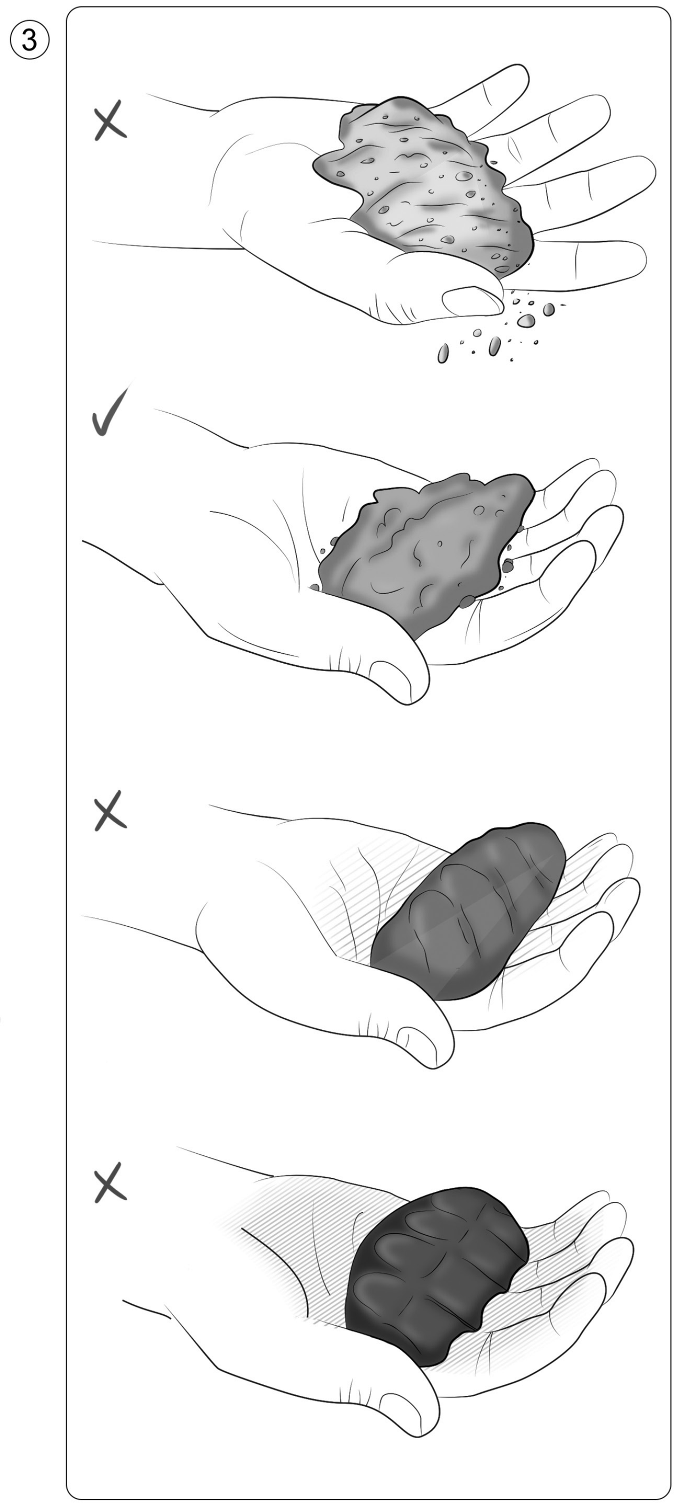
[2] Cast or ball is formed by squeezing soil in hand

See also:

USDA, Natural Resources Conservation Service. 1998. Estimating Soil Moisture by Feel and Appearance. Program Aid Number 1619. *www.nrcs.usda.gov/wps/portal/nrcs/detail/mt/newsroom/?cid=nrcs144p2_056492*

Appendix 4 (cont.): Estimating Soil Moisture By Feel





Using the "squeeze test" to estimate soil moisture

Illustrations by José Miguel Mayo

Appendix 5: Critical Periods for Soil Water Stress by Crop

Apples: During spring growth, flowering, fruit set and development

Arugula: During vegetative growth

Basil: Maturity, to prevent stress-induced flowering

Beans: Flowering, seed set, pod development

Beets: Regular water as roots develop

Broccoli: Head development

Brussels Sprouts: Vegetative and sprout development

Cabbage: Head development

Carrots: Early root development, regular water to prevent cracking

Cauliflower: Head development

Cilantro: During vegetative growth

Collards: During vegetative growth

Corn: During crown root development, at pollination and kernel development

Cucumbers: Flowering and fruit development

Eggplant: All stages

Fennel: Bulb development

Kiwifruit: During spring growth, flowering, and fruit set

Leeks: All stages

Lettuce, head: Head development, pre-harvest

Lettuce, leaf: All stages, pre-harvest

Melons: Flowering and fruit set

Onions, garlic, shallots: During bulb enlargement

Parsley: All stages

Parsnips: Early root development

Peas: Flowering, pollination, pod enlargement

Pears: During spring growth, flowering and fruit set

Peppers: All stages, but allow dry-down between waterings

Plums: During spring growth, flowering, fruit set and development

Potatoes: Tuber enlargement, from flower to die-back

Pumpkins: Flowering, fruit set and development

Radishes: All stages

Small grains: During crown root development, heading, flowering

Squashes (summer and winter): Flowering, fruit development

Tomatoes: All stages, but especially flowering and fruiting

Flowers: Bud development through flowering, and pre-harvest

Appendix 6: General Irrigation Rules

- *During the flowering and fruit set stages of crop development,* plants are most sensitive to drought/water stress.
- *Most crops require irrigation when the soil moisture in the root zone of the plant has decreased to ~50% of field capacity.* Use Appendix 4, Estimating Soil Moisture By Feel, to help you determine the moisture content of the soil.
- *Seed beds containing small-seeded, directly sown crops require light and frequent water applications.* Apply water each time 50% of the surface soil has dried down, showing discoloration (see Appendix 6, Garden-Scale Seed Bed Irrigation in Unit 1.4, Transplanting and Direct Seeding).
- *Seed beds containing large-seeded, directly sown crops require less frequent water applications.* Apply water each time the soil at the depth of the seed has dried to 50% of field capacity. Use Appendix 4 to help you determine the moisture content of the soil.

ADDENDA TO THE GENERAL RULES

1. *Potatoes:* Phase 1 and phase 4 (the planting and maturation stages) require the full soil moisture fluctuation between 50% and 100% of field capacity. Phase 2 and phase 3 (tuber initiation and enlargement) demand less of a fluctuation, responding favorably to a moisture swing between 75% and 100% of field capacity.
2. *Other Solanaceae family crops* (e.g., tomatoes, peppers, eggplant) respond favorably to a full swing between 50% and 100% of field capacity
3. *Cut flowers:* Irrigation 24 hours prior to harvest will help assure full turgor pressure at harvest time and increase the vase life of the stems or bouquets
4. *Leafy greens:* 50% of field capacity minimum
5. *Alliums:* 50% of field capacity minimum
6. *Established fresh beans and peas:* 50% of field capacity minimum
7. *Celery* responds favorably to a moisture swing between 75%–100% of field capacity
8. It is important to *calculate irrigation system uniformity.* This information is critical for accurate determination of irrigation application rates; see Appendix 3: Calculating Distribution Uniformity (DU)
9. *For best yield, turgidity and post harvest handling of brassicas, lettuce, leafy greens and carrots* it is advisable to irrigate as close to harvest as possible, especially during warm weather
10. *Over application of irrigation water* will increase cost of production, limit deeper rooting of some crops, potentially leach water-soluble nutrients from the root zone, enhance weed pressure, and enhance soilborne and foliar disease pressure
11. *Delivery system design* is critical when utilizing well water when the pump delivers water directly to the delivery system

Appendix 7: Irrigation for Various Vegetable Crops

SHALLOW ROOTS – 6 to 24 inches

MEDIUM ROOTS – 24 to 40 inches

DEEP ROOTS – more than 40 inches

Arugula: Frequent shallow water to maintain flavor and succulence and support rapid growth.	SHALLOW
Asparagus: Water deeply and infrequently. Allow to dry down between watering.	DEEP
Basil: Somewhat thirsty. Important to water prior to harvest.	MEDIUM
Beans, fresh: Can drink lots of water because they are fast growing. Once fruit is set, can often "finish" the crop with less or no water to enhance flavor. Vulnerable to disease with overhead water.	MEDIUM
Beans, dry: Treat as fresh beans until seeds begin to mature, then gradually cease application of water.	SHALLOW
Beets: Give adequate supply of water as lack thereof during warm weather causes plants to bolt or beet roots to crack and become tough and woody.	MEDIUM
Broccoli: Commercial growers use 1-1-1/2" per week. Extra water during crown development will add bulk to the harvest.	SHALLOW
Brussels Sprouts: Not very efficient at water uptake so require evenly moist soil to function at best. 70-80% of the roots are concentrated at top 8-12" of soil.	SHALLOW
Cabbage: Needs even moisture or heads will crack. Not very efficient at water uptake.	SHALLOW
Cabbage, Napa: Keep ground moist.	SHALLOW
Carrots: Need deep watering until later stages of root development, at which time excess water can cause roots to crack. Cracking is also caused by too great a fluctuation between wet and dry.	MEDIUM
Cauliflower: Keep soil evenly moist.	SHALLOW
Celeriac: Thirsty like celery, but more tolerant of wet/dry swings.	SHALLOW
Celery: Thirsty; needs frequent irrigation to get well established. Do not overhead water because susceptible to fungal disease. Heavy feeder.	SHALLOW
Chard: Likes moist roots, bolts from water stress.	MEDIUM
Cilantro: Keep moist to forestall bolting.	SHALLOW
Corn: Adequate moisture is critical from tasseling through kernel formation and harvest. Do not over water dry corn (e.g., popcorn and ornamental) at maturity; let it dry out on stalk.	SHALLOW
Cucumber: Sensitive to disturbance. Needs consistently moist soil, watered at base. Susceptible to fungal disease spread through wet leaves. Lack of water when fruits are developing will cut down on production.	SHALLOW TO MEDIUM
Eggplant: Need sufficient moisture. Will always benefit from supplemental fertility.	MEDIUM
Fennel: Likes adequate moisture but not demanding.	MEDIUM

Appendix 7 (cont): Irrigation for Various Vegetable Crops

SHALLOW ROOTS – 6 to 24 inches
MEDIUM ROOTS – 24 to 40 inches
DEEP ROOTS – more than 40 inches

Flowers: Root depth and water needs vary by species. Generally important to supply regular water during bud formation and flowering.

Garlic: Likes steady supply of water. Stop watering several weeks before harvest to reduce succulence and therefore reduce rot during drying. SHALLOW

Kale: Average water needs, except during warm weather when more water is required to prevent wilting. MEDIUM

Kohlrabi: Must have even moisture to be tender. SHALLOW

Leeks: Never let the soil dry out. SHALLOW

Lettuce: Water consistently to avoid bitter taste. SHALLOW

Musk melons: Like a constant supply of moisture. Susceptible to foliar disease, so avoid overhead watering. MEDIUM

Onions: Steady supply of moisture; if too dry, onions get a strong unpleasant flavor. Avoid water on leaves to minimize downy mildew. SHALLOW

Parsley: Somewhat thirsty. SHALLOW

Parsnips: Water lovers. DEEP

Peas: need adequate moisture at flowering and pod enlargement. Avoid water on leaves to minimize mildew. MEDIUM

Peppers: Constant and even moisture from flower through fruit. Peppers like to dry down before being watered again. Will always benefit from supplemental fertility. MEDIUM

Potatoes: Even moisture. This is especially critical during period of tuber enlargement which begins at blossom. Cut back on water as vines die back, to cure the skins. SHALLOW

Pumpkins: Water deep and infrequent. DEEP

Radishes: Need adequate moisture – dry soil results in tough, woody radishes, and vulnerability to flea beetles. Moisture swings cause cracking. SHALLOW

Rutabaga: Provide even moisture. Roots will become tough as a result of the development of extra xylem cells if always forced to bring water up from a deep soil level. DEEP

Salad mix: Water consistently for succulent growth and to avoid bitter taste. SHALLOW

Spinach: Keep evenly moist to forestall bolting. SHALLOW

Squash, summer: Rapid growth and ongoing fruit production requires frequent deep water. MEDIUM

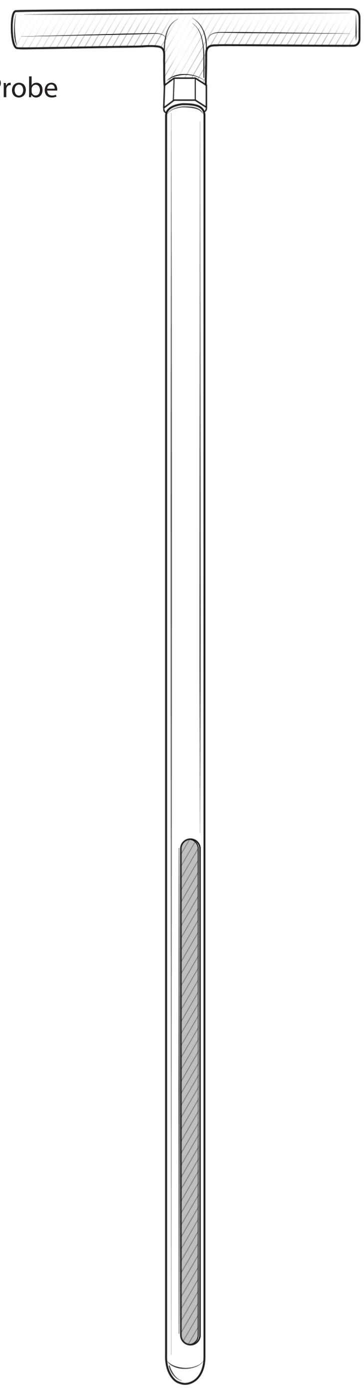
Squash, winter: Do well with deep and infrequent waterings. Avoid overhead water to prevent foliar disease. DEEP

Tomatoes: Like to dry down before being watered again. When blossoming begins, keep soil moisture a little bit drier. Imbalances of moisture may lead to blossom end rot and fruit cracking. DEEP

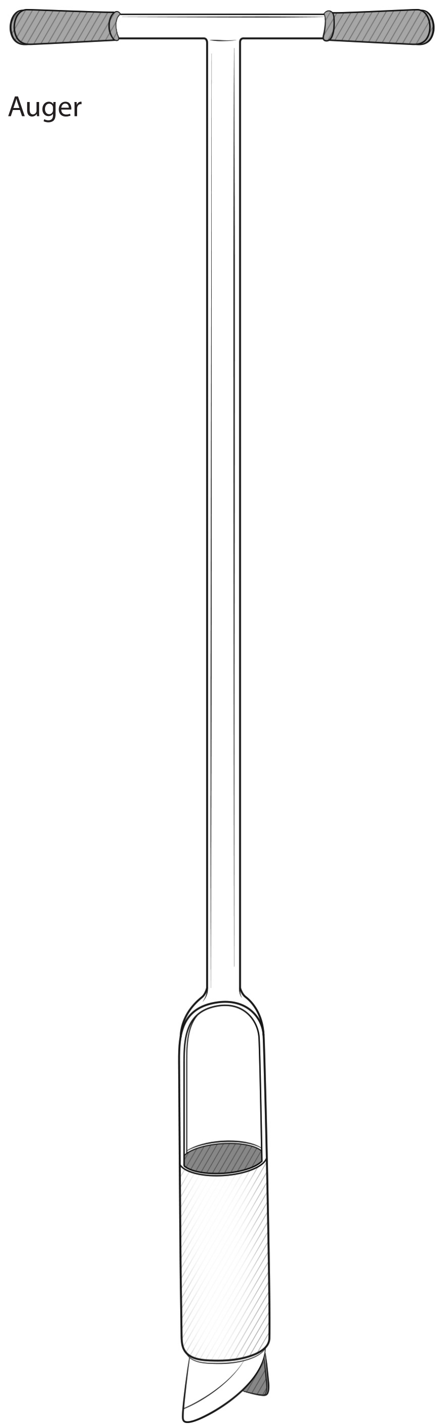
Turnips: Roots will become tough as a result of the development of extra xylem cells if always forced to bring water up from a deep soil level. MEDIUM

Appendix 8: Soil Probe & Soil Auger

Soil Probe

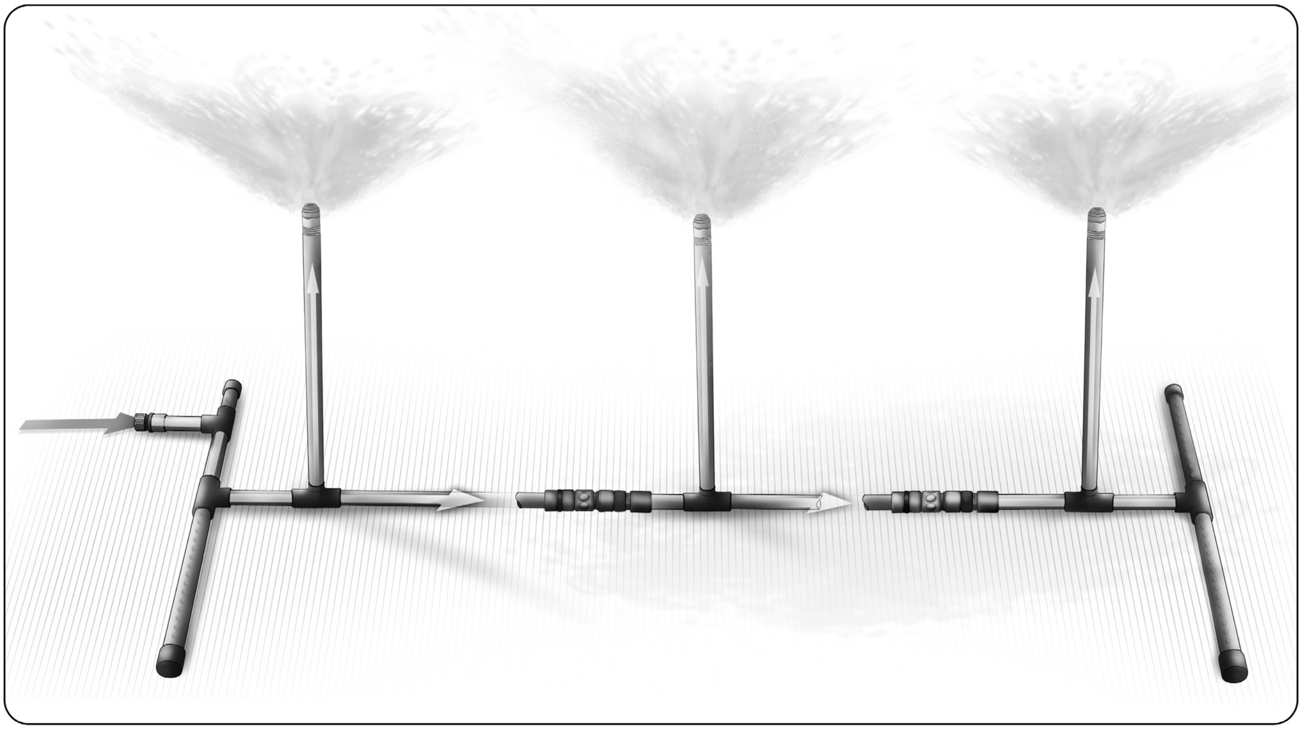


Soil Auger



Illustrations by José Miguel Mayo

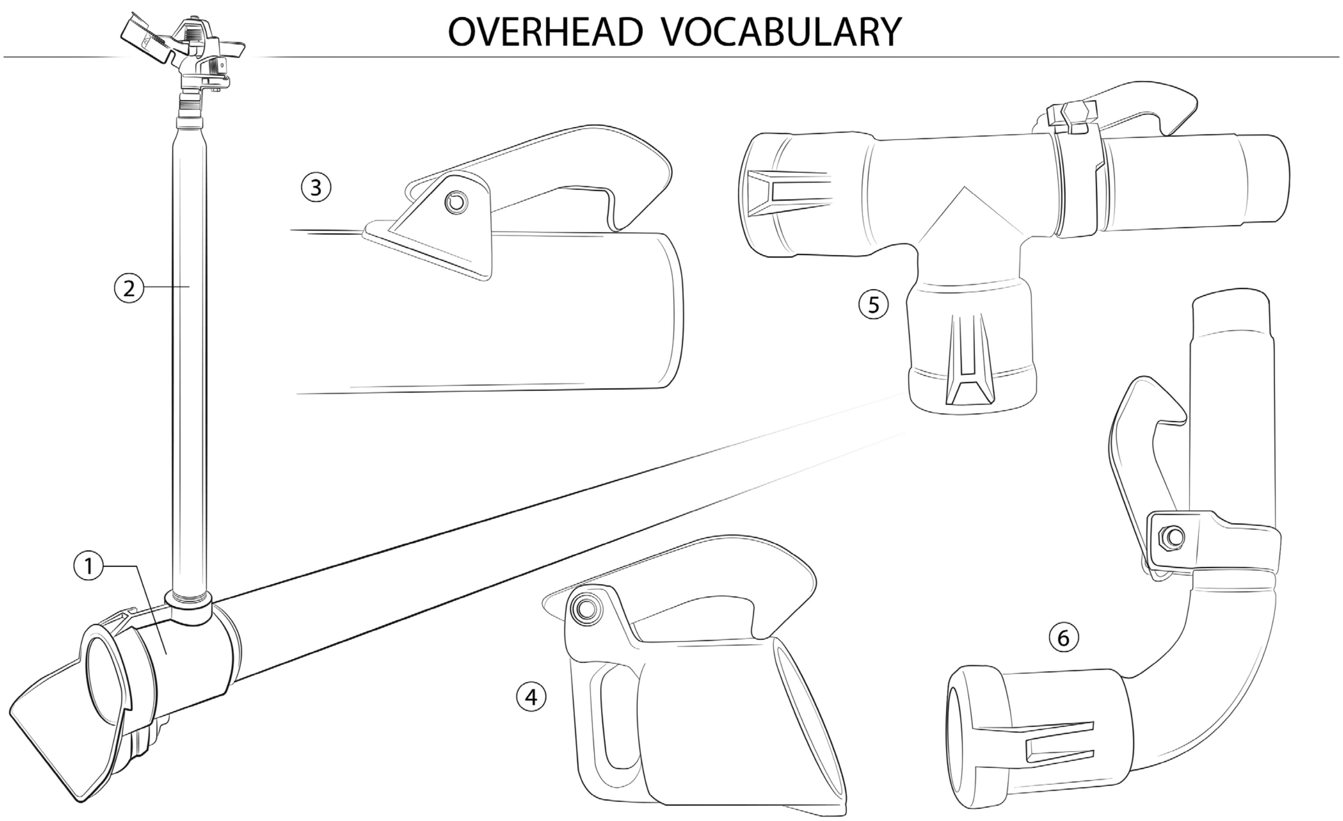
Appendix 9: Irrigation System Components



An easy-to-build, portable riser system of PVC and micro sprinklers can be used to irrigate garden beds.

Illustration by José Miguel Mayo

Appendix 9 (cont.): Irrigation System Components



(1) Overhead aluminum irrigation pipes deliver water to fields. Pipes (also called joints) commonly come in three sizes (2", 3" and 4")

(2) Impact heads (also known as sprinkler heads) come up from the main pipe and release water over the field. Risers connect impact head to pipes. If necessary, valves can be added to risers to shut off individual sprinklers.

(3) Latches connect pipes to each other and to end caps, T's and elbows.

(4) End caps seal off the open end of a line of pipe.

(5) and (6): T's and elbows are used to connect pieces of pipe together.

Illustrations by José Miguel Mayo

Appendix 10: Field Irrigation Schedule

CROPS/FIELD	DATE	TIME	AMOUNT (INCHES)	IRRIGATION METHOD	COMMENTS

Appendix 11: Garden Irrigation Schedule

CROP/BED	DATE	TIME	AMOUNT (INCHES OR TIME)	IRRIGATION METHOD	COMMENTS

Appendix 12: Amount of Water Needed to Pre-Irrigate a Dry Soil to Different Depths (Approximate)*

SOIL TYPE	INCHES WATER PER FOOT SOIL DEPTH	INCHES WATER TO REACH 6 FEET DEEP
CLAY	1.4–1.8	8.6–10.8
SILTY CLAY	1.6–1.9	9.6–11.4
SANDY CLAY	1.6–1.9	9.6–11.4
SILTY CLAY LOAM	2.2–2.3	13.0–13.7
CLAY LOAM	2.0–2.2	12.2–13.0
SANDY CLAY LOAM	2.0–2.2	12.2–13.0
SILT-LOAM	1.8–2.0	10.8–12.2
LOAM	1.7–1.9	10.1–11.4
VERY FINE SANDY LOAM	1.7–1.9	10.1–11.4
SANDY LOAM	1.1–1.3	6.5–7.9
LOAMY VERY FINE SAND	1.1–1.3	6.5–7.9
LOAMY FINE SAND	1.0–1.2	5.8–7.2
LOAMY SAND	0.7–1.0	4.3–5.8
VERY FINE SAND	0.7–1.0	4.3–5.8
FINE SAND	0.7–1.0	4.3–5.8
SAND	0.7–1.0	4.3–5.8
COARSE SAND AND GRAVEL	0.4–0.7	2.2–4.3

* Based on available water holding capacity; plants have dried soil to permanent wilting point, 15 ATM. Assumes the soil is uniform throughout irrigation depth.

Appendix 13: Sample Sprinkler & Drip Tape Application Rate Calculations

Sample sprinkler application rate calculation

You determine your sprinkler risers put out **3.5 gpm** ***(gallons per minute)*** at **60 psi**

30 x 30 spacing = 64 risers per acre

64 risers x 3.5 gpm = 227.5 gpm

227.5 gpm x 60 = 13,650 gph ***(gallons per hour)***

There are 27,154 gallons of water per acre inch

27,154 divided by 2 = 13,577 gallons

So, 13,650 gallons per hour = approximately .5 inch application rate per hour

If your application uniformity is 80% then your application rate is closer to .4 inches per hour (.5 x 80%)

Sample drip application rate calculation

Flow rate: .75 gpm per 100 feet @ 8 psi
(from label)

Bed spacing 2 feet

Bed length 100 feet

218 beds per acre

218 beds x 100 feet = 21,800 bed feet per acre

Total bed feet divided by 100 = 218 100-foot sections per acre

218 sections x .75 gpm (per 100 feet) = 163.5 gpm

163.5 gpm x 60 minutes per hour = 9,810 gph

9,810 gph = 2.76 hours to apply one acre inch
27,154 gallons per acre inch divided by 9,810 gph = 2.76 hours