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Precision Irrigation Technologies for Water-Wise and Climate Resilient Alfalfa Production

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The future of water-wise and resilient alfalfa production lies in the integration of precision irrigation technologies and innovative water management strategies. With the continued threat of drought and depleting levels within the Ogallala aquifer in regions like the Southern Great Plains of the United States, it is important to adopt precision techniques that optimize water use while maximizing crop yields and quality. From soil moisture-based management to canopy-based monitoring and the development of irrigation decision support systems, farmers and CCAs have many options from commercially available tools at their disposal to navigate water scarcity challenges. The power of artificial intelligence, satellite imagery, and real-time data analytics can all be integrated together to bring the agricultural community to work towards a future where alfalfa production remains resilient and environmentally sustainable. Earn 1.5 CEUs in Soil & Water Management by reading this article and taking the quiz at https://web.sciencesocieties.org/Learning-Center/Courses.

The toll of drought on agricultural production has been staggering in the Southern Great Plains of the United States, with an adjusted average loss of $8.1 billion per year between 1980 and 2023 (Figure 1). The Ogallala Aquifer, the largest source of water in the region, spans parts of eight states. Annually, this region generates more than $20 billion in revenue, accounting for over 95% of total groundwater withdrawals and covering approximately 27% of all irrigated land. Around 14% of the irrigated agricultural land within the Ogallala Aquifer basin is dedicated to alfalfa cultivation.

Alfalfa holds a prominent position as the third most profitable field crop in the United States, covering 14.9 million acres with an average yield of 3.2 tons per acre (Natzke, 2023). It is widely used as cattle feed due to its adaptability, long growing season, ability to be harvested multiple times, high yield, excellent forage quality, and significant economic value (Baral et al., 2022). Alfalfa is rich in essential nutrients, including proteins; vitamins A, C, E, and B; minerals; and dietary fibers. Its roots can reach depths of 8 to 12 feet, providing remarkable drought tolerance and achieving a water productivity of 30.3 lb/ac/inch.

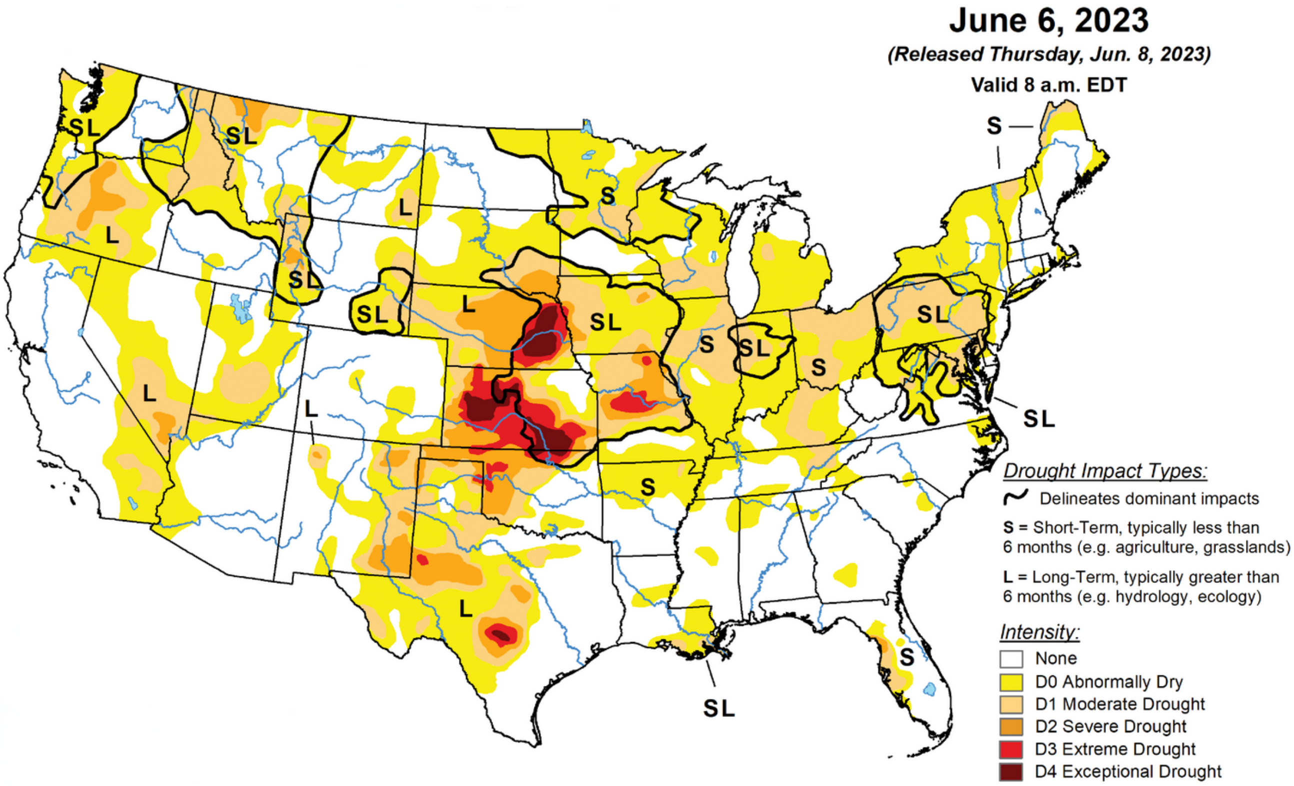

Figure 1. Drought map of United States (Source: Drought.gov, 2023).

Despite its potential, a significant yield gap of 54–60% remains, with potential yields ranging from 4.9 to 10.4 tons per acre. To address drought-related challenges and maintain both the quantity and quality of alfalfa production, precision irrigation technologies play a crucial role in applying the concept of “more crop per drop.” By implementing precision irrigation techniques tailored to alfalfa’s specific water requirements and utilizing advanced monitoring and control systems, producers can improve water efficiency, mitigate the negative impacts of drought, and ensure the sustainability of alfalfa production.

Alfalfa, known for its high water requirement, typically needs between 20 and 46 inches of water per growing season. This requirement varies based on environmental conditions, altitude, length of the growing season, number of harvests, latitude, and the fall dormancy rating of the alfalfa cultivar. A proactive strategy is essential to mitigate the negative effects of drought-induced anomalies on agricultural systems, as many producers are considering a shift toward more water-efficient cropping systems. Given that alfalfa is a major forage crop for the beef and dairy sectors, addressing water management issues with long-term solutions is critical for its continued sustainability.

Soil-Moisture-Based Water Management

With frequent drought and high water demand of alfalfa, it is important to manage irrigation with optimized and informed strategies. Measuring soil moisture to irrigate alfalfa fields is commonly used and is an important method for using water resources wisely to achieve economically viable production. The management allowable depletion in alfalfa is 0.50–0.60, which means the crop will start to experience moisture stress and potential yield reduction when 50–60% of total available water is depleted. The recommended soil matric potential value at management allowable depletion of alfalfa ranges from 80–150 kilopascals (kPa) or 11.6 to 21.8 pounds per square inch (psi). This range is particularly suitable for clayey and sandy soil, respectively. Soil matric potential is the force that binds water molecules to solid particles and to each other in soil pores. Very commonly, tensiometers are used to measure soil matric potential in unsaturated conditions, and water present in the soil under tension is quantified.

A tensiometer can be 6–35 inches in length. Commercial tensiometers available include Meter—Teros 32; Irrometer—SR, LT, and MLT; and Soil Moisture Equipment Corp. Jet Fill—2710ARL and 2725ARL. Each sensor costs around $80–250, and transducers range from $140–200. Tensiometers work well in sandy soils but have a slow response time to water changes. Time domain reflectometry (TDR) works well in clay and loamy soils with quicker response to water changes using dielectric constant (▯) of water to determine the volumetric water content of the soil. This sensor consists of two to three parallel rods that generally range from 4 inches to 3.3 ft in length inserted into the soil. An accuracy of ± 0.01 ft^3/ft^3 can be achieved through TDR soil moisture meters. Some of the commercially available TDR soil moisture meters are Trase TDR (Soil Moisture Equipment Corp.), FieldScout TDR 300 and TDR 350 (Spectrum Technologies); Acclima TDR-315N and TDR-310W; Acclima Digital True TDR-310N and TDR-315H; and Campbell Scientific CS655 and CS616.

Each sensor and datalogger costs within the range of $250–350 and $500–2,500, respectively. Farmers and CCAs can install soil moisture sensors at different depths and various field locations to get an overview of the soil moisture level at a particular time interval. Only the top 3–4 ft of the root zone is considered for irrigating alfalfa, but alfalfa roots can remove water from much deeper soil layers.

Figure 2. Collecting thermal and multispectral images of alfalfa.

Canopy-Based Water Management

Canopy-based water management is a better strategy than depending on direct measurement of soil water content. Loss of water from the canopy matrix and surfaces or evapotranspiration (ET) considers water loss from both soil (evaporation) and plant leaves (transpiration). The ET is influenced by meteorological factors like air temperature, relative humidity, wind speed, solar radiation, and crop growth and health. Daily ET reports can be found from nearby weather stations. Generally, weather stations use alfalfa as a reference crop to report reference ET (ETr), and if not, calculations must be made to modify the ET value into crop ET (ETc). Seasonal ET of alfalfa varies with location. Satellite data are often used to develop ETr maps on a grid, which can be paired with alfalfa's crop coefficient (Kc) value to estimate the ETc of a particular growing season. Remote sensing generally offers a quick, economical, non-destructive, and spatiotemporal measurement of different physiological, biochemical, and structural canopy parameters at various scales, i.e., ground, aerial, and satellite. Alfalfa plants may be stressed before visual symptoms of water stress appear. It is possible to prevent significant reduction in alfalfa production and forage quality by detecting physiological changes in plants through different remote-sensing methods. The multispectral remote-sensing methods that are used to identify plant responses to limited water stress include visible-near-infrared reflectance (VNIR; 380–1000 nm) and shortwave infrared reflectance (SWIR; 900–1700 nm). Thermal imaging (TIR; 8–14 μm) detects radiation in the infrared wavelength range and displays false-color images where pixels contain temperature values (Figure 2). If the temperature detected from the thermal image pixels is higher than the normal crop canopy temperature of alfalfa, this implies the level of crop stress under drought.

Ongoing efforts to develop open-access ET tools like OpenET (https://etdata.org/) have been instrumental in making decisions on the water requirements of alfalfa and other crops in the currently validated regions for this tool. With satellite data from Landsat, canopy surface temperature from thermal images, and meteorological data from weather stations, high-resolution mapping of evapotranspiration can be created based on the surface energy balance model. Precision irrigation techniques like the combination of thermal maps (from UAV or satellite), multispectral imagery (from UAV or satellite), and weather data (from local weather stations) can be used to create high-resolution (about 3.3 to 8.2 ft) surface temperature maps on a subfield scale to understand the water stress of the crop at every georeferenced coordinate in the field. However, spatial ET maps have a limitation in making comparisons between the intervals of image collection, which makes water management based on ET challenging.

Daily evapotranspiration reports can be found from nearby weather stations, which is useful for canopy-based water management. Photo courtesy of Adobe Stock/kinwun.

Canopy temperature detection is crucial in understanding drought stress in alfalfa. When the crop water status is low, the crop reduces its transpiration rate by regulating the stomatal aperture. This results in higher leaf temperature compared with the canopy temperature of a well-watered alfalfa. Canopy temperature measurement is influenced by air temperature, humidity, wind speed, vapor pressure deficit, and incoming radiation, which limits the measurement reliability. As a solution, numerous crop water stress indices are developed to estimate plant water stress accurately and remotely. Stress Degree Day was developed to consider air temperature for normalization of canopy temperatures. A further improved index is the Crop Water Stress Index (CWSI), where the upper baseline (canopy temperature of a non-transpiring crop) and the lower baseline (canopy temperature of a fully transpired crop) are created to calculate the index. The CWSI is adaptable to any crop under any meteorological condition as it indirectly considers air temperature, wind speed, vapor pressure deficit, radiation, and humidity. Other than CWSI, the Water Deficit Index (WDI) is used to measure crop water stress using a combination of vegetation indices (such as NDVI and SAVI) and canopy temperature. Another derivative of CWSI is the thermal index of relative stomatal conductance, which directly calculates, based on canopy temperature, net isothermal radiation, air temperature, wind speed, and relative humidity.

Various unoccupied aerial vehicles (UAVs) and satellites equipped with advanced sensors have been developed for image capture purposes. Some popular satellites with high resolution widely used in agricultural production systems include Landsat-8 (98.4 ft), Sentinel-2 (33–197 ft), Sentinel-3 (984 ft), and MODIS (820 ft). These satellites offer spatial images free of cost, making them accessible for various applications. However, for higher-resolution images, there are satellites like PlanetScope, offering resolutions as fine as 9.8 ft, with a cost of $1.4/mi^2. Similarly, WorldView-4 provides exceptional resolution at 12.2 inches but at a higher cost of $13.9/mi^2. The flight altitude for UAVs depends on the desired spectral resolution. For example, 2.1 inches per pixel of multispectral images can be generated from Altum-PT if flown at a 394 ft altitude. The resolution can be increased by flying the UAV at a lower altitude. The Altum-PT also generates high-resolution RGB (Red-Green-Blue) and thermal images. Some multispectral and hyperspectral sensors available on the market include Resonon Pika L, ATLAS, TIMS, AHI, HyperCam-LW, HyTES, and SEBASS.

Alfalfa cannot endure prolonged flooding and thrives in soils with a pH of 6.5 or higher. Deep, well-drained, medium-textured soils like sandy loam, silty loam, and clay loam are preferred for alfalfa cultivation due to their optimal water-holding capacity and aeration. Photo courtesy of Adobe Stock/peter.

Irrigation Decision Support System for Alfalfa

In the advent of precision agriculture tools and techniques, web-based telemetry systems are enabling producers and CCAs to make informed decisions without the need to physically visit fields. Commercial sensors are now seamlessly integrated with cloud-based data storage units, facilitating the sharing of information via internet protocol or cloud services through both mobile applications and web interfaces. The integration of soil moisture or canopy moisture status data with telemetry that can be interpreted and then translated to make decisions forms the basis of an irrigation decision support system (IDSS).

There are two types of soil-based IDSS, based on how water content is measured in soil. Type 1 employs sensors that gauge volumetric water content, reporting data in terms of weight or volume percentage, or as inches of water per foot of soil. On the other hand, Type 2 sensors measure matric potential, expressing values in bars or kilopascals (kPa). These sensors, typically offered by vendors alongside telemetry services, provide real-time data on crucial irrigation parameters like soil moisture, temperature, and conductivity. This sensor data is stored in cloud-based applications, accessible easily via mobile phones, allowing producers to optimize water usage and irrigation scheduling. By using this information, producers can increase or maintain production while minimizing water wastage or during shortages. Some examples of commercially available sensors are Sentek Drill and Drop probes, Irrometer tensiometers, Goanna Ag systems, and Soil Scout systems. These soil-based IDSS technologies represent a game-changer for resilient alfalfa production, offering producers the tools they need to make informed decisions and maximize crop yields while conserving water resources.

Similar to soil moisture monitoring, alfalfa producers often monitor physiological and metabolic processes such as stem or leaf water potential, relative moisture content, stomatal conductance, and canopy temperature to assess plant water status. Commonly used indices for water stress include canopy temperature, canopy cover, and stem water potential. Canopy-based IDSS can help in determining irrigation timing, crop water requirements, soil salinity stress, and controlled stress to improve crop quality and health. These sensors, however, can lack information on soil moisture and evaporative demand, thus rendering them less useful for estimating irrigation requirements (Jha et al., 2022). Plant-based IDSS are often integrated with meteorological parameters and evapotranspiration data to enhance accuracy in water management decisions. Commercial sensors like Arable Mark 3 and Tule, with their telemetry systems, namely Arable Open, Arable Mobile, and Tule Web, are commercially available in U.S. markets.

For soil- and canopy-based IDSS, it is important to acknowledge that limited water availability can reduce plant height, leaf number, leaf area, and internode length in alfalfa. Prioritizing maximum alfalfa leaf growth is essential as leaves contain more protein and less fiber, contributing to better feed quality and therefore higher return on investment. Optimal water usage is vital for improving alfalfa yield and forage quality. Considering water quality and soil type is crucial for effective water management, as poor irrigation water can adversely impact alfalfa production, quality, and soil health. Alfalfa exhibits moderate sensitivity to salinity, similar to corn. Factors such as climate, soil texture, cultural practices, and irrigation management influence the threshold salinity tolerance levels of alfalfa. Alfalfa cannot endure prolonged flooding and thrives in soils with a pH of 6.5 or higher. Deep, well-drained, medium-textured soils like sandy loam, silty loam, and clay loam are preferred for alfalfa cultivation due to their optimal water-holding capacity and aeration.

Figure 3. Drone flight in the alfalfa-sown rainout shelter plots in Manhattan, KS.

Research Underway: Drought-Resilient Alfalfa Production

On-farm research is being conducted by researchers at Kansas State University and Texas A&M University in the irrigated areas of Kansas, in collaboration with industry, farmers, and stakeholders, to achieve digital solutions in precision water management for alfalfa production and forage quality. Baselines will be developed by assessing canopy temperature in alfalfa using thermal images collected through UAVs to measure CWSI in alfalfa. High-resolution spatial water stress maps will be generated utilizing predictive evapotranspiration modeling, and changes in forage quality due to limited irrigation will be recorded. To mimic drought conditions, the study is conducted in the rainout shelters of the K-State Agronomy Research Farm (Figure 3). The study outcomes will support farmers and CCAs in adopting precision water management strategies to enhance sustainability and farmer profitability.

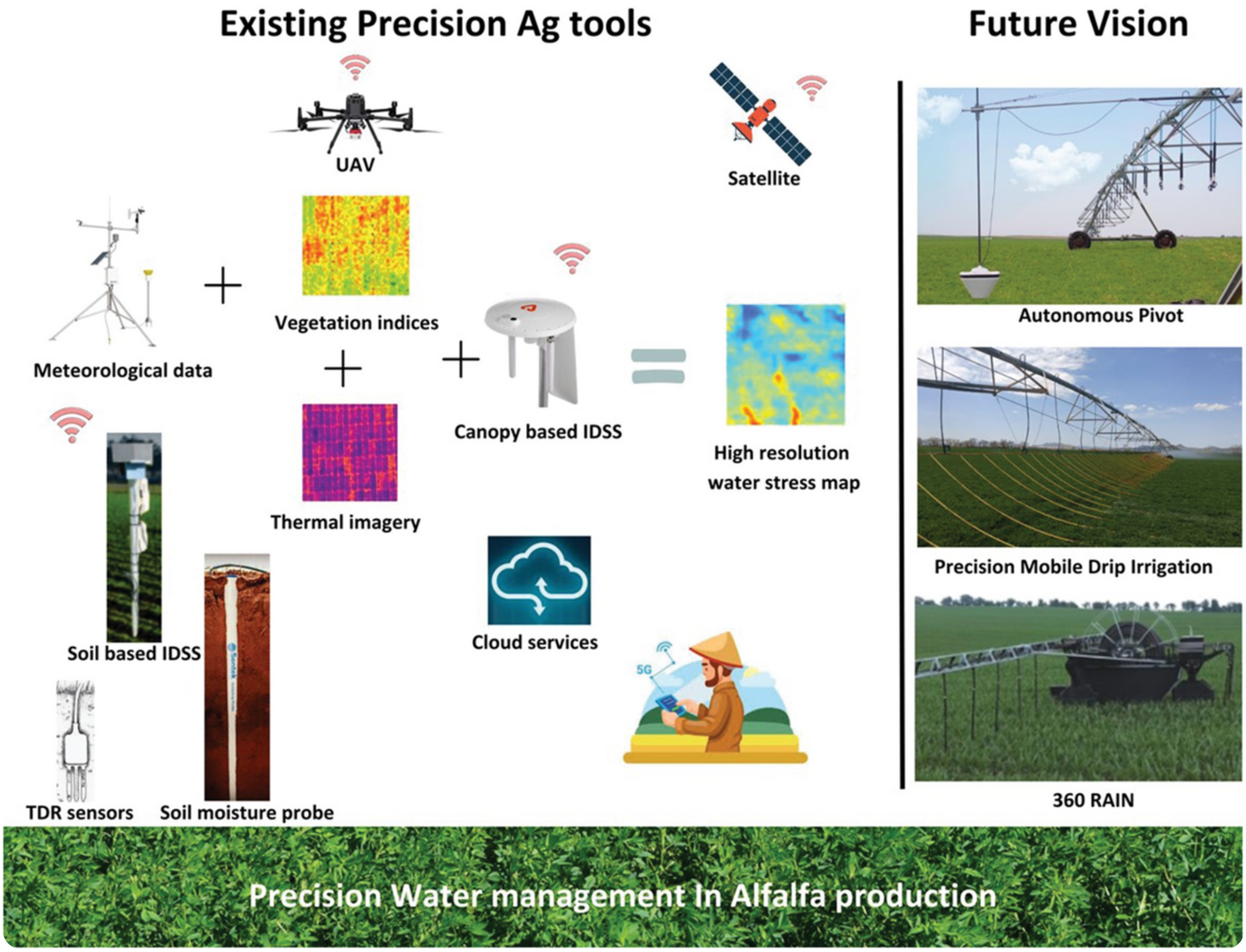

Figure 4. Existing precision agriculture tools and their future vision in alfalfa production.

Future Vision of Precision Agriculture in Water Management

Advancements in agricultural technology are revolutionizing water management practices, particularly for crops like alfalfa in water-stressed regions such as Kansas, Nebraska, and Texas. One such innovation is the integration of artificial intelligence into center-pivot irrigation systems. This technology, exemplified by the Autonomous Pivot, utilizes ground-penetrating radar to assess crop water needs in real time without disturbing the soil. Farmers can remotely control and monitor irrigation operations through user-friendly web applications, enhancing efficiency and resource utilization.

Another significant development is Precision Mobile Drip Irrigation (PMDI), designed to optimize water distribution in both center- and linear-pivot systems (Figure 4). The dripline is attached to the pivot system and dragged through the crop behind the system, delivering uniform water flow. Water is applied directly to the soil surface, potentially saving 20–30% of water and reducing inefficiencies due to uneven surfaces and wind drift. DripNet PC is used to operate, monitor, and maximize the performance of the PMDI system.

The center- or lateral-pivot systems, however, are not feasible in irregularly shaped fields with uneven corners. **360 RAIN** provides the "million-dollar rain" on any day of the growing season in any size of the field if wells can provide 100–225 gallons of water per minute to the system. It is a three-wheeled electric vehicle that receives a signal from a satellite through real-time kinematic technology and can apply 1 inch of rain over an 80-acre field at a speed of 0.45 miles per hour per week. **360 RAIN** can work with wells or reservoirs, operating with 75% less flow capacity than a traditional pivot.

Despite advancements, irrigating irregularly shaped fields precisely can be challenging. To address this challenge, precision irrigation technologies controlled by computer vision, such as **360 RAIN**, have been developed. This mobile solution is guided by real-time kinematic satellite signals, enabling it to autonomously navigate fields and accurately apply water where necessary. The system operates efficiently with less water compared to traditional methods, resulting in substantial water savings while ensuring crops receive optimal hydration.

The future of water-wise and resilient alfalfa production lies in the integration of precision irrigation technologies and innovative water management strategies. With the continued threat of drought and depleting levels within the Ogallala Aquifer in regions like the Southern Great Plains of the United States, it is important to adopt precision techniques that optimize water use while maximizing crop yields and quality. From soil moisture-based management to canopy-based monitoring and the development of irrigation decision support systems, farmers and CCAs have many commercially available tools at their disposal to navigate water scarcity challenges. The power of artificial intelligence, satellite imagery, and real-time data analytics can all be integrated to bring the agricultural community together in working toward a future where alfalfa production remains resilient and environmentally sustainable.

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1. **What is the future vision for water-wise and resilient alfalfa production?**
   a. To rely solely on traditional irrigation methods.
   b. To integrate precision irrigation and innovative water management strategies.
   c. To abandon alfalfa production altogether.
   d. To increase water consumption without considering sustainability.

2. **What is the water productivity of alfalfa in drought conditions?**
   a. 20.4 lb/ac/inch.
   b. 25.6 lb/ac/inch.
   c. 30.3 lb/ac/inch.
   d. 40.2 lb/ac/inch.

3. **What is the primary reason for the extensive use of alfalfa in cattle feed?**
   a. Its adaptability to low temperatures.
   b. Its ability to grow in saline soils.
   c. Its high nutritional value and yield potential.

d. Its resistance to drought conditions.

4. **Time domain reflectometry (TDR) soil moisture meters use dielectric constant to determine soil water content.**
   a. True.
   b. False.

5. **How many states does the Ogallala Aquifer span across?**
   a. Four.
   b. Six.
   c. Eight.
   d. Ten.

6. **Which satellite provides spatial images free of cost?**
   a. PlanetScope.
   b. Landsat-8.
   c. Sentinel-2.
   d. Both b and c.

7. **What is the primary function of tensiometers in soil moisture monitoring?**
   a. Measuring air temperature.
   b. Monitoring soil salinity.
   c. Quantifying soil matric potential.
   d. Assessing crop health.

8. **Which of the following is NOT a factor influencing evapotranspiration (ET)?**
    a. Relative humidity.
    b. Soil moisture.
    c. Wind speed.
    d. Crop growth.

9. **What is the purpose of developing high-resolution spatial water stress maps?**
    a. To increase water usage.
    b. To reduce the cost of irrigation.
    c. To understand crop water stress at every georeferenced coordinate in the field.
    d. To eliminate the need for irrigation altogether.

10. **The primary goal of precision irrigation techniques is**
    a. to maximize water usage, regardless of crop needs.
    b. to minimize water usage, regardless of crop needs.
    c. to maximize water usage based on specific needs of the crop.
    d. to minimize water usage based on specific needs of the crop.

11. **Alfalfa has shallow roots, making it highly susceptible to drought stress.**
    a. True.
    b. False.

12. **Water stress in crops like alfalfa can be accurately detected through canopy temperature measurements.**
    a. True.
    b. False.

13. **Landsat 8 offers higher resolution imagery compared with Sentinel 2.**
    a. True.
    b. False.

14. **Canopy-based irrigation decision support systems are typically integrated with meteorological data to enhance accuracy.**
    a. True.
    b. False.

15. **Weather stations can be used to monitor daily evapotranspiration (ET) rates.**
    a. True.
    b. False.
