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Article

More efficient sources of water distribution for agricultural and general usage

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SUMMARY

Current irrigation systems that disperse water above ground waste an enormous amount of fresh water. Since fresh water is a limited resource, new irrigation systems are desperately needed to make agriculture more sustainable. To investigate this issue, we tested two new watering systems for water efficiency and successful plant growth compared to traditional overhead sprinklers, systems that spray droplets of water (similar to rainfall) from above, with sesame plants. One system utilizes an underground pipe to distribute water intermittently; the other utilizes an underground cloth saturated with water to provide a continuous and gradual diffusion of water to plants. We hypothesized that both underground methods would be more efficient than the sprinkler method, saving more water and resulting in comparable plant growth. Given that sesame plants have been shown to prefer well-drained soil (and do not do well in standing water), we suspected that the cloth method would be more effective at delivering the minimal amount of water needed for these plants. We found that the underground cloth-based water diffusion method saved more water compared to the other distribution systems; however, it also resulted in a slight reduction of the yield (plant growth). The underground pipe-based water distribution system outperformed the sprinkler system (used less water); however, it still produced the same yield. Based on these experimental results, we propose substitution of the conventional overhead sprinkler watering system with underground methods such as a pipe-based water distribution system or cloth-based water diffusion system to conserve water.

INTRODUCTION

Water is a resource that is seemingly plentiful given that 71% of the earth's surface is covered with water; however, 97% of this water is too salty for nearly all usages, leaving a mere 3% of water available for use as fresh water (1). Fresh water, being in limited supply, will inevitably be used up due to pollution/contamination, the depletion of reservoirs, and the increase in demand due to the growing human population (2). Getting and dispersing clean, drinkable water across the world is an expensive undertaking, and one that will only get more expensive as demands rise. Irrigation accounts for over 70% of water usage globally (3, 4). Many of the irrigation methods used today are surface irrigation methods, meaning water is applied above ground. Although these methods are generally easier to install and repair, they can lose 40-50% of the expelled water due to wind, evaporation, run-off, and deep percolation (where water sinks below the level of the root system and is therefore out of useful range) (5). Of the surface irrigation methods, the most popular are sprinkler systems and furrow irrigation. However, in both of these methods, the level of water (and slope of the fields) has to be carefully maintained in order to optimize water efficiency and the effects of these methods can vary widely depending on the region and soil consistency (1, 6, 7). Another popular option for surface irrigation that is slightly more water efficient is the drip irrigation method. In this method, the water falls onto the soil directly above the plant in little amounts over time instead of a large amount of water at once, resulting in less water usage, less chance of overwatering which results in run-off and deep percolation, and less water loss from evaporation. Drip irrigation is currently one of the most efficient watering systems to date. However, it is currently applied to less than 5% of irrigated property in the world (8). This may be because although the drip method conserves water, it can be very expensive to install, and the dripper lines are prone to getting clogged (9). In addition, oftentimes drip irrigation does not provide enough water to plants in places that can be arid and/or windy. The top of the soil may become dry and firm in these conditions, killing the plants, or the heat can cause mineralization of the drip lines, which then clog (10). Some experts have suggested placing mulch or another soil-like material over the topsoil to reduce evaporation and improve water absorption (10). These studies suggest that an underground method of delivering water may be ideal.

In 2014, an article in *Resilient Agriculture* outlined a new plan for what is called drainage water management, which employs structures underground to help lower and raise the natural water table levels in the soil (11). However, this method does not work well in areas where the ground is not level and can require a substantial amount of water if the starting point for water table level is considerably low (12). Newer methods of subirrigation have recently begun to be investigated due to their water efficiency and observed improvements in plant growth (13). One of these methods, the trough method, places plants in a slanted trough to allow water to flow from one end of the row to the other where it is collected. Water passes through the root zone of the plants which are placed in pots with holes in them to allow absorption of water through the roots. The drawback of this method is that it can only be used for plants in pots or plants placed in an above ground structure (such as equipped greenhouses) that can be easily slanted. Therefore, this method would not work for larger-scale crop use (13). Another method that has been suggested is a capillary mat system. This method uses a fabric mat that is kept continuously wet and is placed under the plants near their roots (13). So far, this method has only been used in greenhouses and with plants in pots, but in this study, we wanted to investigate the quantitative differences between subirrigation methods like this one and above ground methods such as the sprinkler system.

Due to increasing temperatures and decreasing rainfall, many areas are experiencing worsening draughts, making water efficiency research more important now than ever before (14). In this study, we sought to compare the effects of three methods of water delivery on plant growth. For this, we used a traditional overhead sprinkler system and two underground methods: an intermittent underground pipe system where water is delivered through holes in pipes (similar to the trough method or a typical drip method but underground), and a cloth method (similar to the capillary mat system) where water is fed to the soil continuously by installing a damp mat below the surface of the soil **(Figure 1)**. We devised this mat, using a piece of cloth from a shirt, to reduce evaporation and to avoid blockage issues commonly reported in drip and pipe delivery methods. We also hoped that by soaking the mat in water, it would self-regulate the amount of water delivered to the plants through natural capillary diffusion. In addition to plant growth, the amount of water used in each method was also measured to determine which method was more water-efficient.

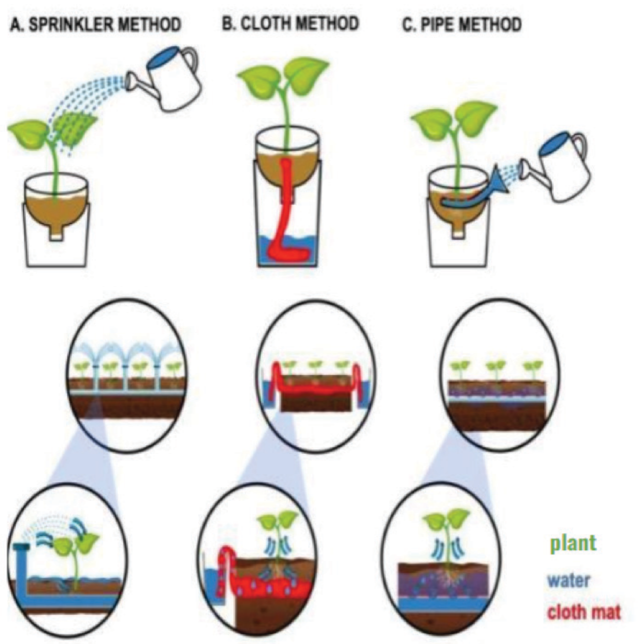

Figure 1: Diagram of three water delivery systems tested. The top three images show a single plant system, grown in a half liter bottle cut in half. The circles below each method indicate what each of these methods would look like on a larger scale with multiple plants. Blue arrows indicate the direction of water flow. In the Sprinkler Method (A), water was delivered by a watering can from overhead. In the Cloth Method (B) a cloth (red) is soaked in water and placed under the plant. In the Pipe Method (C), water is delivered to a pipe with evenly spaced holes that is placed under the plant. Images of plants used in this figure came from Freepik (19).

We hypothesized that underground watering systems would be more efficient, in that they would save more water and produce a similar yield (plant growth) because water is not lost to evaporation or wind when delivered underground. Second, we hypothesized that the cloth method would be more efficient than the underground pipe method because the water delivery is self-regulating, allowing for the system to save as much water as possible. Our results suggest that both of our hypotheses were correct. We found that of the three watering systems, the overhead sprinkler system utilized much more water than the underground watering methods, although all three systems produced similar plant growth. In addition, the underground pipe system, which delivered water intermittently, did not save as much water as the underground cloth system, which provided water continuously through natural diffusion. These results suggest that an underground cloth watering system would be the more water-efficient model for plant irrigation in the future.

RESULTS

For this study, we tested the effects of three different watering systems on plant growth using one biological replicate for each system. Given that sesame plants have been shown to prefer well-drained soil, we hypothesized that the underground cloth method would be the most effective at delivering the minimal amount of water needed for these plants and therefore the most efficient for plant growth (15). To test this hypothesis, we grew sesame seeds under three different watering conditions, including a traditional overhead sprinkler system, where water was delivered periodically from overhead **(Figure 1A)**, a cloth method where water was given continuously underground with an absorbent cloth **(Figure 1B)**, and an intermittent underground pipe system, where water was delivered through holes in pipes underground **(Figure 1C)**. For each system, water was either continuously provided (the continuous underground cloth system) or given on an as-needed-basis.

We compared the three different watering systems over the course of 40 days. The sprinkler system, where water was given from overhead, consumed the most water at 2.0 liters of water **(Figure 2, Table 1)**. The continuous underground cloth system, where water was given through cloth, consumed the least amount of water at 0.4 liters of water **(Figure 2, Table 1)**. The intermittent underground pipe system used a total of 1.3 liters of water **(Figure 2, Table 1)**. Although all three systems did not receive the same amount of water, the

	Sprinkler Method	Cloth Method	Pipe Method
Total Water (liters)	2.0	0.4	1.3
% water saved compared to Sprinkler Method	N/A	81%	32%
% water saved compared to Pipe Method	-68%	73%	N/A

Table 1: Water consumption values for Sprinkler, Cloth and Pipe watering methods. N/A indicates no comparison could be made.

	Sprinkler Method	Cloth Method	Pipe Method
Plant Growth (centimeters)	11.4	10.2	11.4
% growth increase compared to Cloth Method	11%	N/A	11%

Table 2: Plant growth observed for Sprinkler, Cloth and Pipe watering methods N/A indicates no comparison could be made. Since the sprinkler method and the pipe method have equivalent growth, there is no need for a second comparison.

resulting plant growth was quite similar **(Figure 2, Table 1)**. Watering via the overhead sprinkler system resulted in the highest plant growth of 11.4 centimeters, while watering with the continuous underground cloth system produced slightly less growth at 10.2 centimeters **(Figure 2, Table 1)**. The intermittent underground pipe system however, despite utilizing less water than the overhead sprinkler system, resulted in 11.4 centimeters of plant growth, equivalent to the overhead sprinkler system **(Figure 2, Table 1)**.

Although all three systems resulted in similar plant growth, the intermittent underground pipe system saved 32% of water volume compared to the overhead sprinkler system **(Table 1)**.

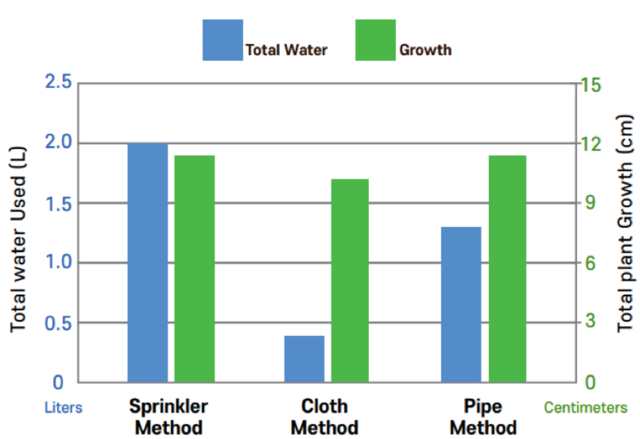

Figure 2: The cloth method produced near equal plant growth but used the least amount of water of the three methods. Bar graph illustrating the total water consumed in liters (left axis, blue bars) and total plant growth in centimeters (right axis, green bars) for three different systems tested (n = 1 plant measured per system).

The continuous underground cloth system saved 81% of water volume compared to the overhead sprinkler system and 73% of water volume used in the intermittent underground pipe system **(Table 1)**. Growth-wise, although the continuous underground cloth system used less water, plants watered with the overhead sprinkler system and the intermittent underground pipe system grew 11% more than those watered with the continuous underground cloth system **(Table 2)**. Using the values above, we calculated the efficiency of each plant's growth compared to the amount of water usage. The calculated efficiency of each system revealed 5.8 centimeters of plant growth per liter of water for the overhead sprinkler system, 29.0 centimeters per liter for the continuous underground cloth system, and 8.9 centimeters per liter for the intermittent underground pipe system **(Figure 3)**.

DISCUSSION

One might assume that the amount of provided water may directly correlate with yield, i.e., plant growth. In contrast, the experimental results of this paper suggest that the correlation between the amount of supplied water and plant growth is low. From our data, we conclude that although all three watering systems resulted in similar plant growth, the amount of water required for this growth was very different. The overhead sprinkler system utilized more water than the intermittent underground pipe system; nonetheless, they both exhibited the same amount of yield, i.e., plant growth, which was the maximum expected size of 11.4 centimeters. Further, the continuous underground cloth system used less water than the overhead sprinkler system or the underground pipe system; however, it resulted in an equivalent amount of plant

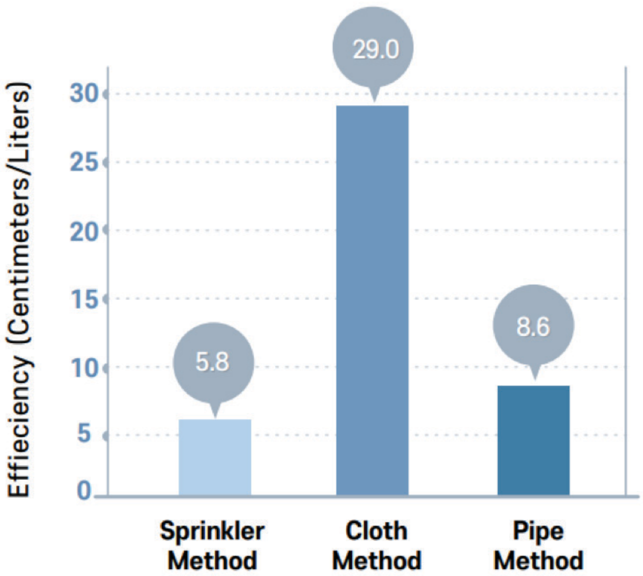

Figure 3: The continuous underground cloth system had the greatest growth per liter of water making it the more efficient watering system. Bar graph illustrating the efficiency of plant growth (centimeters grown per liter of water consumed) for three different systems tested. n = 1, one plant per system measured.

growth. Overall, the continuous underground cloth system turned out to be the most efficient watering system of the three without any sacrifice in plant size.

Regarding future experiments, there are a few follow-up measures that could be tested due to limitations of the current study. Although this study showed promising results, this study consists of only one biological replicate (with one plant per condition). To add confidence to these results, this experiment should be repeated by independent scientists with multiple biological replicates in order to improve the statistical confidence level and identify outliers. With any experiment, numerical results typically fall within a normal distribution with the most common, or "mean" values clustered in the middle, with outlier possibilities on the outside (create the shape of a symmetrical peak). Therefore, while it is likely our measurements fell close to the average, we cannot rule out that it is possible they were closer to an outlier value, which is why multiple biological replicates would add confidence to our data and our interpretations. As more biological replicates are added, a more accurate measurement of the mean can be achieved. Another limitation of this study was the experiment length. Our study was 40 days long, which was long enough to detect significant growth from each plant. However, we could have extended this period to get more information about long-term effects of each watering method. Although part of the goal in this experiment was to determine which system would utilize the least amount of water with comparable levels of plant growth, another possible future experiment could instead provide the same amount of water in each system (maybe using the cloth method as a maximum to prevent overwatering the plants in that condition), and then measuring plant growth in addition to measures such as soil humidity. Indeed, soil humidity measurements during this experiment would have been a valuable way to more accurately predict when additional water should be provided and to monitor the efficiency of each watering method. In addition, it would be valuable in future studies to measure additional growth features such as a change in mass, width, and size of leaves, as well as the growth rate over time. Further, although this study was specifically done with sesame plants, we would predict similar results with other species of plants. It would be particularly interesting to test these systems in growing grains that require a lot of water (such as rice, soybeans, and wheat) since with these crops even more water could potentially be saved (16). Another plant that would be beneficial to test with subirrigation are almonds, since they have been reported to require an enormous amount of water. In California alone, almond crops require as much water each year as the entire city of Los Angeles over a 3-year timespan (17). Unfortunately, due to the length of these experiments, it was not feasible for us to redo the experiments with these modifications in mind. However, we hope that others find these suggestions useful in considering their own future experiments.

In the future, to gain insight into the impact of this study, experiments will need to be compared at a much larger scale. Conducting large-scale experiments will be necessary to test the cost, usability, and reliability of these watering methods to determine if they are realistically viable. Although sprinkler systems are currently being used in large-scale applications, our subirrigation methods are not. Therefore, further research would need to be conducted to determine the best way to adapt these methods for large-scale applications. One important aspect to consider is the specific materials used to make employment of these methods as cost-efficient as possible. For employing a large-scale underground pipe system, different types of mesh or material that could help prevent soil and other materials from seeping into the pipe should be tested. Different materials used for pipes could also be considered when planning a large-scale version of this experiment since that can directly affect cost and maintenance. One would also need to compare the efficiency between a pump system versus a gravitational system to push water from one end of the pipes to the other over large distances. While pipes are more likely to experience blockages, especially in a large-scale application, the cloth system would eliminate issues with blockages. It would be necessary, however, to run small pipes or some kind of reservoir to supply water for the mat to ensure that it is constantly damp. It is also important to consider that outdoor conditions (weather, humidity, etc.) could impact the results of different irrigation methods greatly, and the amount of water needed may vary. For all large-scale experiments, it will also be necessary to consider the time, complexity, and maintenance costs to build to maximize the utility and efficiency of these watering systems.

Fresh water is a limited resource on earth. It is a necessity for terrestrial life, but sadly, much of our water is wasted. Forty percent of the freshwater used to grow crops globally is lost in the environment (5). Current flaws in surface irrigation systems used in agriculture and personal use result in water loss through run-off, evaporation, and inefficiencies in water/sprinkler management (5). Without proper management, water either disperses into areas where it is not needed or evaporates from the surface. Even though this loss may seem minimal, when multiplied by millions of acres of land, this loss is drastic. In fact, it has been shown that sprinklers can lose up to 50% of applied water due to evaporation (6). This loss also means people are spending more money than they need for water, and if they changed watering methods, they could decrease costs significantly.

The cloth system presented here utilizes natural adhesion and cohesion forces in order to slow water release while still being able to provide enough hydration for growth. As the water makes its way through the cloth, it also disperses into the soil allowing for plants to take up the water from the cloth or the soil in its vicinity. Given that both underground watering methods produced a similar amount of plant growth, we show that underground watering systems may be more efficient. Given that approximately 7.5 quadrillion liters of water are used annually for agriculture worldwide, we estimate that if we applied the cloth system to all agriculture, the system would have the potential to save 2.3 trillion cubic meters of freshwater a year (this estimate was calculated by comparing current water use to the percentage of water saved with the cloth method in our experiment compared to the sprinkler system) (5).

MATERIALS AND METHODS

Watering Systems

The overhead sprinkler system **(Figure 1A)** used here represented the conventional sprinklers that are commonly used. Plants were supplied with water from above via a small watering can with approximately 1 mm diameter exit holes to emulate sprinklers spraying water from above. The continuous underground cloth system **(Figure 1B)** represented an underground fluid-absorbing mat. This mat was made from a repurposed cotton t-shirt and was connected from a water source to the plant container (ran along the inside of the plant container before going underneath the plants). The mat was placed approximately 5–7.5 centimeters below the plant seeds and was in direct contact with the soil. Lastly, the intermittent underground pipe system **(Figure 1C)** utilized an underground pipeline that provided water for the plant. The plastic pipe was placed approximately 5–7.5 centimeters below the plant seeds and contained small (approximately ⅔ centimeter) holes at regular intervals (approximately 2.5 centimeters apart) on multiple sides of the pipe to allow water to exit the system. The pipe was also wrapped with a thin layer of cotton cloth so that dirt would not go into the pipe or clog the holes. Water was continuously provided in the continuous underground cloth system or given on an as-needed-basis for the pipe and sprinkler systems.

For the overhead sprinkler and pipe method, water was distributed with distinct 0.35-liter water bottles and only a fraction of the total bottle was administered in order to achieve soil saturation. The amount of water given via both of these methods was determined by observing the point until the soil was thoroughly damp (seen through the clear container) and stopping when so. For the cloth method, water was provided continuously which was dispersed into the soil by natural diffusion (a cloth in a reservoir of water was threaded into the lower layers of soil). Once the bottle for a particular watering method was empty, it was refilled. The plants were monitored daily and watered on an as-needed-basis to achieve a consistent level of soil moistness. Therefore, we observed that the overhead system utilized more water in order to fully saturate the soil compared to the pipe system. Every time the water bottle was emptied, a note was made so that total water consumption could be tracked (these rates varied per watering system). On the last day of the 40-day experiment, the amount of water left in the current bottle was subtracted from 0.35 liter and added to previous consumption to estimate the total amount of water used over the course of the experiment.

Plant Growth/Conditions

For all three systems, the same species of plant (sesame seeds from Zion Market) were used. Sesame seeds were used due to their high disease and insect tolerance while also being cost-effective. Sesame plants are both fast-growing and can get substantially tall which would help produce reliable results in a shorter time period (1, 18). Initially, multiple (3–5) sesame seeds were planted into each system. Each system was constructed by cutting a plastic water bottle 0.5 L bottle) in half, filling halfway with soil, and was adjusted to simulate an overhead sprinkler system, cloth system, or underground pipe system. On day 1, sesame seeds were planted and watered as described above. Once it was confirmed that the plants were growing successfully, all the plants in each system but the two largest plants were removed. This led to there being two plants in each system. In order to control for slight variations in the initial/early stages of plant growth from a seed and also out of possible competition that the two plants could experience so close to each other in the system, we focused our measurements solely on the first plant to sprout above the soil, which was therefore the tallest plant to gather measurements for our graphs. Seventeen days after seed planting, we moved all the plants into a larger version of their current watering system (from 0.5-liter water bottles to 1.0 liter-sized water bottles) to allow the plants more room to grow.

The soil used in the experiments was obtained at Lowe's and the water was provided by the tap water of Orange County Water District. For all three watering systems, plants were placed side-by-side close to a window to minimize differences in light, temperature, and other climate factors.

Data Analysis

We kept track of plant growth and water usage in a Google spreadsheet. Here we collected data daily and recorded our findings. All calculations were made in Google Sheets and graphs were made using a combination of Google Sheets and Google Slides.

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REFERENCES

1. California-Great Basin, Bureau of Reclamation. “Water Facts - Worldwide Water Supply.” *California-Great Basin,* Bureau of Reclamation, www.usbr.gov/mp/arwec/water-facts-ww-water-sup.html.
2. Heggie, J. “Why is America Running out of water?” *National Geographic,* 2020, www.nationalgeographic.com/science/article/partner-content-americas-looming-water-crisis.
3. Hares, Sophie. “The Cost of Clean Water: $150 Billion a Year, Says World Bank.” *Reuters,* 28 Aug. 2017, www.reuters.com/article/us-global-water-health/the-cost-of-clean-water-150-billion-a-year-says-world-bank-idUSKCN1B812E.
4. Balsom, Paul. “Water Usage in The Agricultural Industry.” *High Tide Technologies,* 28 Sept. 2020, htt.io/water-usage-in-the-agricultural-industry/.
5. Green, Jenny. “Which Type of Irrigation Loses the Most Water to Evaporation?” *Home Guides,* SF Gate, 10 Mar. 2014, homeguides.sfgate.com/type-irrigation-loses-water-evaporation-100415.html.
6. “Surface Irrigation Systems.” *Oklahoma State University,* 1 Feb. 2017, extension.okstate.edu/fact-sheets/surface-irrigation-systems.html.
7. Surface Irrigation Systems. www.fao.org/3/T0231E/t0231e04.htm.
8. Martinko, Katherine. “How Drip Irrigation Can Save the World.” *Treehugger,* 13 Dec. 2016, www.treehugger.com/how-drip-irrigation-can-save-world-4856721.
9. “Why All Farms Don’t Use Drip Irrigation.” *Water Footprint Calculator,* 28 Apr. 2020, www.watercalculator.org/footprint/farmers-use-drip-irrigation/.
10. Dunn, Elizabeth G. “A Tiny Piece of Plastic Is Helping Farmers Use Far Less Water.” *Bloomberg Businessweek,* 22 Sept. 2021, www.bloomberg.com/news/features/2021-09-23/how-microdrip-irrigation-systems-use-less-water-and-could-change-farming-forever.
11. Frankenberger, J. “Drainage Water Management in the Corn Belt.” *Resilient Agriculture,* vol. 14, no.15, Aug. 2014.
12. Drainage Water Management. www.nrcs.usda.gov/wps/portal/nrcs/detail/?cid=nrcs144p2_027166.
13. “Subirrigation Systems.” *Center for Agriculture, Food, and the Environment,* 6 Mar. 2015, ag.umass.edu/greenhouse-floriculture/fact-sheets/subirrigation-systems.
14. Harvey, Fiona. “Are we running out of water?” *The Guardian,* 18 June 2018, www.theguardian.com/news/2018/jun/18/are-we-running-out-of-water.
15. Sesaco Sesame Coordinators, Langham, R., Riney, J., Smith, G. & Wiemers, T. *Sesame Growers Guide,* Sesaco, 2008, www.sesaco.net
16. “Which Crops Consume the Most Water?” *MSFAgriculture,* 18 Jan. 2020, msfagriculture.com/2020/01/18/which-crops-consume-the-most-water/.
17. Lurie, Julia. “California Almonds Suck as Much Water Annually as Los Angeles Uses in Three Years.” *Mother Jones,* 12 Jan. 2015, www.motherjones.com/environment/2015/01/almonds-nuts-crazy-stats-charts/.
18. Associated Press. “Southern Farmers Experiment With Growing Sesame.” *AG Web Farm Journal,* Sept. 2014, www.agweb.com/news/crops/crop-production/southern-farmers-experiment-growing-sesame
19. “Free Vector: Life Cycle of Green Bean.” *Freepik,* 13 Dec. 2017, https://www.freepik.com/free-vector/life-cycle-green-bean_1470971.htm?query=growth.