doi:10.2489/jswc.2022.00088

Cover crops may exacerbate moisture limitations on South Texas dryland farms

S. Kasper, F. Mohsin, L. Richards, and A. Racelis

Abstract: Cover crops are a sustainable management tool for mediating weed pressure, reducing soil erosion, and enhancing soil organic carbon (C) and nitrogen (N) levels. Yet, adoption rates across water-limited farms in Texas remain low, especially among producers without irrigation access, due to concerns that cover crop use of soil moisture will negatively impact subsequent cash crop yields. This three-year cover crop trial in a rain-fed sorghum (*Sorghum bicolor* L.) farm in Lyford, Texas, trialed different cover crop mixes and seeding rates and confirmed that cover cropping leads to significant soil moisture deficits and cash crop failure when rainfall is low between cover crop termination and cash crop planting (<30 mm). In seasons one and three, moisture deficits contributed to significantly lower germination of post–cover crop sorghum compared to fallow control plots. In season two, increased precipitation during a longer moisture recharge period between cover crop termination and cash crop planting helped avoid sorghum yield drops. Length of recharge period, amount of rainfall, species selection, planting density, and termination method are major determinants of subsequent cash crop outcomes. Careful management can minimize some of the risks cover cropping poses to soil moisture, but without reliable rainfall at key points in the cropping cycle, cover cropping remains risky for farmers without irrigation access.

Key words: cover crop—dryland farming—moisture—semiarid—soil health

Cover crops are a conservation agriculture practice in which plants are grown as an investment in future soil health rather than for immediate harvest (Fageria et al. 2005; Snapp et al. 2005). When well-implemented, cover crops can benefit both farm economics through reduced input costs and increased yields as well as the environment through decreased nutrient and sediment runoff and improved climate resilience (Yoder et al. 2021). After one to three years of implementation, cover crops regularly increase soil aggregate stability, microbial biomass, and nitrogen (N) mineralization rates (Stewart et al. 2018), and over time can lead to higher soil organic carbon (C) levels, particularly in medium and fine textured soils (Jian et al. 2020). A metanalysis covering 377 studies over 32 years of cover crop research found that cover cropped soils had an advantage over fallow areas for most ecosystem services measured including reduced soil erosion, nitrate (NO_3^-) runoff, bulk density and weed pressure as well as increased soil C, microbial biomass, arbuscular mycorrhizal fungi levels, and cash crop yields (Daryanto et al. 2018).

In aggregate, the benefits of cover cropping to agroecosystem health are promising. However, these benefits can be complicated by regional climate and economic contexts. Many examples of cover crop success are from humid and subhumid areas or irrigated farms where plant growth is not usually limited by moisture (Berrada and Roseberry 2018). In an overview of 27 recent publications on cover cropping in semiarid areas with 250 to 500 mm of annual precipitation, Nielsen et al. (2016) noted yield declines after cover cropping in 53 out of 61 of the reported studies. Yield declines occurred more often in the southern United States than in the northern United States and Canada, likely due to increased evapotranspiration rates in the hotter southern regions (Robinson and Nielsen 2015).

For this reason, many farmers remain skeptical about the benefits of cover crops, especially where moisture is a limiting factor. Adoption rates in the Lower Rio Grande Valley (LRGV), a semiarid region at the southernmost tip of Texas where 66% of the cropland is unirrigated (USDA NASS 2017), remain low due to farmer concerns that cover crop moisture use might negatively impact the yield of subsequent cash crops. The climate of the Rio Grande Valley is similar to other warm, semiarid regions where cover crop–induced moisture deficits have reduced cash crop yields (Unger and Vigil 1998; Kaspar and Singer 2011) and soil moisture is a primary limiting factor for plant growth in this region. Minimal research on cover crops has been conducted in the LRGV and the trials that have been published rely on irrigation and report little on soil moisture effects (Zibilske and Makus 2009; Moran and Greenburg 2008; Soti et al. 2016; Soti and Racelis 2020). In other regions where cover crop soil moisture dynamics have been studied in greater depth, cover crops have had mixed impacts on soil moisture and evapotranspiration depending on the context. Even within the same field in different years, moisture dynamics vary widely due to differences among cover crops, management practices, and climate, particularly temperature and precipitation (Qi et al. 2011; Sharma and Irmak 2017).

This study assesses cover crop feasibility on nonirrigated land in semiarid, south Texas, a practice with great interest among area growers, despite the moisture concerns expressed in the literature and by some dryland farmers. This on-farm trial measures the impact of 12 total cover crop treatments (5 single species and 7 multispecies mixes) on soil moisture over a three-year period and explores management choices that might mitigate the risk of cover crop induced moisture deficits, including species selection,

Stephanie Kasper is a research associate in the Department of Biology, **Faeqa Mohsin** and **Lindsey Richards** are research assistants in the School of Earth, Environmental, and Marine Sciences, and **Alexis Racelis** is an associate professor in the Department of Biology and School of Earth, Environmental, and Marine Sciences, University of Texas Rio Grande Valley, Edinburg, Texas.

Received May 24, 2021; Revised August 14, 2021; Accepted September 23, 2021.

planting density, termination method, and recharge period length.

Materials and Methods

Study Site and Design. The study was conducted at a USDA certified organic field located in Lyford, Texas (26.365 N, –97.904 W). The soil type for this location is Willacy fine sandy loam (USDA NRCS 2020) with an average field capacity of 23% volume and a water holding capacity of 19% (Thomas et al. 1994). The average annual precipitation is 530 mm with peak rainfall between May and October (NOAA NCEI 2020). The participatory cover crop trial began in fall of 2017, using a complete randomized block design with five replicates of five treatments (four cover crop treatments and a control). Each of the 25 plots was 6 m wide and 100 m long, for a total research area of 1.5 ha.

Cover crop treatments were selected at the start of each trial season in close consultation with the farmer. Treatments with low performance were eliminated, and new candidates were added to provide more useful information for area farmers. Though specific cover crop treatments changed in each of the three years, control plots and cover crop plots maintained consistent locations for all three seasons. Since the cover crop treatments, planting and termination dates, and precipitation levels varied each season, direct comparisons of soil moisture and crop performance are restricted within each project year. The cover crop treatments for the three seasons are listed in table 1 and their scientific names in table 2.

Cover crops were seeded using a Sunflower seed drill (AGCO, Duluth, Georgia) and terminated through tillage with a flail mower followed by a disc bedder. After cover crop termination, sorghum (*Sorghum bicolor* L.) was seeded at 22 kg ha^{-1} using a MaxEmerge no-till planter (John Deere, Moline, Illinois). Dates of cover crop seeding, termination, and sorghum seeding for each season are included in table 3.

Soil Moisture, Germination, and Biomass Measurements. In all three seasons, surface soil volumetric water content (0 to 5 cm) was measured using portable moisture probes (TEROS 12, Meter Group, Pullman, Washington, and ExTech MO750, FLIR Commercial Systems Inc, Nashua, New Hampshire). Measurements were taken at least monthly during the cover crop season. The closest measurement dates to cover crop termination and sorghum planting are used in this analysis. In the third season, a set of 25 TEROS 11 sensors with ZL6 data loggers (Meter Group, Pullman, Washington) were installed in the field, one in each of the 25 plots, to provide in-situ root zone volumetric water content measurements at 10 to 15 cm depth. These sensors were installed on September 26, 2019, and removed on December 10, 2019, before cover crop termination. They were reinstalled on January 8, 2020, and removed on February 24, 2020, to allow for sorghum planting. Sensors were reinstalled on April 9, 2020, after sorghum seeding and remained in the field until sorghum termination on June 8, 2020. The sensors recorded soil moisture and temperature every 15 minutes. Surface soil moisture measurements were unavailable for the sorghum planting date in year three, so 10 to 15 cm depth moisture measurements are substituted for this date only.

Germination rates were measured one month after cash crop seeding each season by counting the number of sorghum seedlings in a 10 m transect with 3 replicates per plot (n = 75). Biomass was measured at the end of each cover crop season using a 0.5 m^2 sampling ring. One sample was taken from each plot (n = 25) in year one and three samples per plot (n = 75) in years two and three. Samples were dried for at least three days at 70°C before weighing. Aboveground and belowground cover crop biomass and weed

Table 1

Cover crop treatments and seeding rate.

	Treatment				
Year	1	2	3	4	5
1	Field pea (135)*	Hairy vetch (17)	Crimson clover (34)	Field pea (56); triticale (56)	Control
2	Cowpea (27); buckwheat (22); collards (4)	Guar (6); Proso millet (9); Tillage radish (4)	Sunn hemp (10); safflower (7); rapeseed (7)	Tillage radish (7); black oats (56)	Control
3	Sunn hemp (50)	Tillage radish (11); hairy vetch (11); black oats (6)	Sunn hemp (20)	Mustard (22); tillage radish (22); cowpea (19); sunn hemp (19)	Control

*(#) = Seeding rate in kilograms per hectare. Scientific names listed in table 2.

Table 2

Cover crop scientific names.

Year	Common name	Scientific name
1	Crimson clover	*Trifolium incarnatum*
1	Field pea	*Pisum sativum*
1, 3	Hairy vetch	*Vicia villosa*
1	Triticale	x *Triticosecale*
2	Buckwheat	*Fagopyrum esculentum*
2	Collard	*Brassica oleracea* var. *viridis*
2	Guar	*Cyamopsis tetragonoloba*
2	Mustard	*Brassica rapa*
2	Proso millet	*Panicum miliaceum*
2	Rapeseed	*Brassica napus*
2	Safflower	*Carthamus tinctorius*
2, 3	Black oats	*Avena strigose*
2, 3	Cowpea	*Vigna unguiculate*
2, 3	Sunn hemp	*Crotalaria juncea*
2, 3	Tillage radish	*Raphanus sativus*

biomass were each weighed separately and then added together for total biomass. The lack of deeper soil moisture measurements in the first two years of this research is an acknowledged limitation. However, surface moisture data are more relevant to the paired cash crop germination measurement than deeper soil moisture, which would impact later stages of cash crop growth.

Data Analysis. All statistical analyses were conducted in R (R Core Team 2019). For moisture measurements at cover crop termination and sorghum planting, data collected for each of the five treatments were divided into two categories: control ($n = 5$) and cover crop ($n = 20$). These two groups were checked for normality and equal variance and then compared using a series of six two-sample t-tests, one comparison for each moisture measurement date in each year. The same process was used for germination data.

Spearman's rank correlation was used to test for relationships during each of the three seasons between the following three variable pairs: (1) biomass and soil moisture, (2) cover crop seeding rate and soil moisture, and (3) soil moisture and sorghum germination. Correlations 1 and 2 used soil moisture at cover crop termination, while correlation 3 used the soil moisture at sorghum planting.

Results and Discussion

Cover cropping resulted in moisture deficits compared to control plots in all three seasons. In the first year, these moisture deficits persisted at the time of sorghum planting and caused declines in sorghum germination and yield. In years two and three, no moisture differences persisted at the time of sorghum planting. Sorghum germinated well in all plots in year two and resulted in comparable yields between cover crops and controls. In year three, however, despite comparable soil moisture at sorghum planting, germination rates were lower in the cover cropped areas than in the controls once again. These results are visually summarized in figure 1 and explained in greater detail in figure 2 and the following sections.

Cover Cropping Results in Soil Moisture Deficits in all Three Years. In each of the three study years, the control plots had significantly higher moisture levels than the treatment plots at the end of the cover cropping period. In year one, mean soil moisture was 7.31% in the control plots and 5.15% in the cover crop plots 67 days after cover crop planting (t [23] = 3.83, $p < 0.001$; figure 2a). Year two was a wetter year with 146 mm of rain during the cover crop season compared to the 24 mm received in year one. However, even with higher rainfall, the pattern of significantly higher moisture in the controls remained 85 days after cover crop planting with 12.72% moisture in the controls and 10.75% in the cover crops (t [23] = 3.50, $p < 0.001$; figure 2b). The trend again appeared in year three, 93 days after planting with 5.21% moisture in the controls compared to 3.48% in the cover crops (t [23] = 5.63, $p < 0.001$; figure 2c).

Moisture Deficits from Cover Cropping Remain at Time of Sorghum Planting in Year One. Moisture deficits after cover cropping are expected because cover crops, like all plants, lose water through evapotranspiration (Unger and Vigil 1998). However, these moisture losses become a risk when they persist until cash crop seeding and moisture availability for sorghum germination remains below a critical threshold (Lu et al. 2000). Whether deficits persist depends on the length of the recharge period between cover crop termination and cash crop planting and the amount of rainfall received during that recharge period. Significant moisture deficits in cover cropped areas remained through the early sorghum season in year one, but not year two or three.

In year one, a late start to the cover cropping season led to a late termination, just

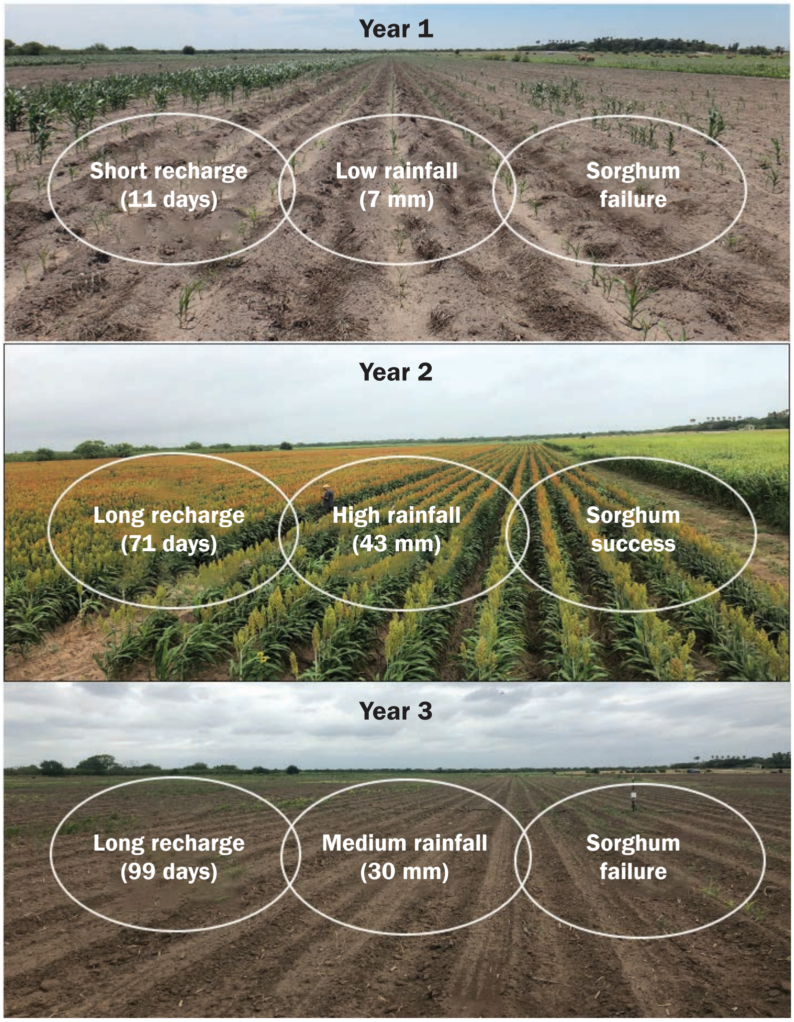
Table 3
Planting calendar and rainfall.

Crop year	Season	Start date	End date	Days	Rainfall (mm)	Average temperature (°C)	
						Max	Min
Year 1:	Cover crop	Nov. 17, 2017	Feb. 24, 2018	100	24.40	22	10
2017 to 2018	Recharge*	Feb. 25, 2018	Mar. 7, 2018	11	7.30	28	17
	Sorghum	Mar. 8, 2018	June 12, 2018	97	56.60	33	19
	Fallow	June 13, 2018	Sept. 24, 2018	115	332.10	36	24
				Total	420.40		
Year 2:	Cover crop	Sept. 25, 2018	Dec. 17, 2018	84	146.10	26	14
2018 to 2019	Recharge	Dec. 18, 2018	Feb. 26, 2019	71	43.30	23	11
	Sorghum	Feb. 27, 2019	Sept. 3, 2019	189	169.12	33	22
	Fallow	Sept. 4, 2019	Sept. 17, 2019	34	32.60	33	23
				Total	391.12		
Year 3:	Cover crop	Sept.18, 2019	Dec. 30, 2019	104	112.60	28	15
2019 to 2020	Recharge	Dec. 31, 2019	Apr. 7, 2020	99	29.70	27	14
	Sorghum	Apr. 8, 2020	June 8, 2020	62	86.36	33	21
	Fallow	June 9, 2020	Sept. 25, 2020	109	673.35	34	23
				Total	902.01		

*Recharge is the time between cover crop termination and cash crop planting.

Figure 1

Visual contrast in three years of sorghum crop following cover cropping. In year one, cover crop moisture usage, followed by insufficient moisture recharge led to sorghum germination declines in the cover cropped areas and total yield loss. In contrast, year two had a longer recharge period with more rainfall before cash crop seeding. Cover cropped areas recovered from their moisture deficits and showed comparable sorghum yields to controls. Year three repeated the long recharge period, but the recharge period saw less rainfall than year two over a longer period. Like year one, sorghum germinated better in the controls and showed declines in the cover cropped areas.



11 days before sorghum seeding. Only 7.30 mm of rain fell during this short recharge period between cover crop termination and cash crop seeding. Moisture measurements 14 days after sorghum seeding showed that the control plots at 5.73% continued to have significantly higher moisture levels than the cover cropped area at 4.13% (t [23] = 7.69, $p < 0.001$; figure 2d).

After the moisture challenges of year one, the farm collaborator requested a much longer gap between cover crop termination and cash crop seeding in year two. The longer 71-day recharge period saw 43.30 mm of rainfall, which fully reset the cover crop moisture deficit by sorghum seeding. The trend of the first year was reversed perhaps due to moisture retention by cover residues in the cover cropped plots. Mean cover crop moisture at sorghum seeding was 17.81% while control plots were 12.10% (t [23] = 4.62, $p < 0.001$; figure 2e).

Year three repeated the long recharge period, this time leaving 99 days between cover crop termination and cash crop planting. However, only 29.70 mm of rain fell during this period spread across multiple small rain events. The farm collaborator delayed planting to wait for more rainfall but conditions remained dry. Despite dry conditions, the field was seeded on April 8, 2020, at the end of the sorghum seeding window. At time of seeding, there were no significant differences in moisture across the treatments in year three. Mean moisture was 8.68% in the controls and 8.37% in the cover cropped areas (t [23] = 0.29, p = 0.77; figure 2f).

Lower Sorghum Germination in Cover Cropped Areas in Years One and Three. Although sorghum is drought-hardy crop that can tolerate major moisture stress during its later growth, moisture stress at seeding can still cause major declines in germination and establishment (Shrestha et al. 2016). Alongside cash crop yield and profit, sorghum germination is a key indicator of whether the cover crop is a benefit or an obstacle to a farm operation.

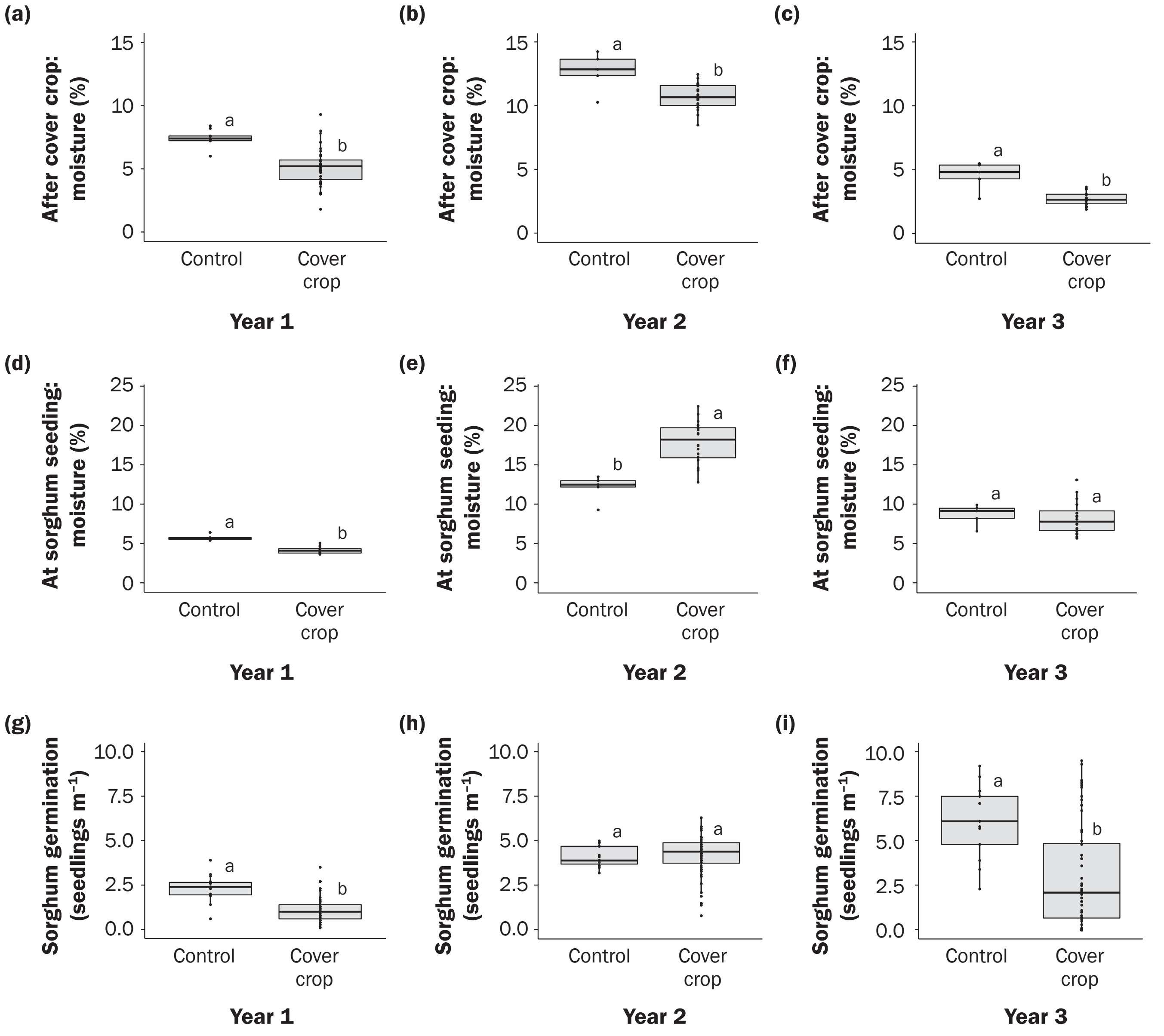
In year one, cover crop treatment had a significant impact on sorghum germination with 2.3 seedlings m^{-1} in the controls and 1.10 in the cover crop plots (t [73] = 6.11, $p < 0.001$; figure 2g). Some of the sorghum that did germinate in the cover crop plots, especially in forage pea (*Pisum sativum* L.) and forage pea/triticale mix planted in year one, exhausted their initial moisture supply and then desiccated. By midseason, only the controls held strong sorghum stands (figure 1). The cover cropped areas were patchy and bare due to the cover crop-induced dry conditions. The farm collaborator considered these fields too poor to harvest and terminated the field by tillage before the remaining sorghum was ready for harvest.

Year two had no significant differences among treatments for sorghum germination. The controls averaged 4.13 seedlings m^{-1} and the cover crops had 4.17 seedlings m^{-1} (t [73] = 0.14, p = 0.89; figure 2h). This result suggests that moisture was not a limiting factor for sorghum germination under the wetter conditions of year two. Year two yielded sufficient sorghum to harvest, but there were no significant differences in yield between cover crop and control (t [43] = 0.28, p = 0.78). The mean yield was 4,747 kg ha^{-1} for the control plots and 4,868 kg ha^{-1} for the cover crop plots.

In year three, soil moisture levels were similar among treatments at sorghum plant-

Figure 2

Impacts of cover cropping on soil moisture and sorghum germination. Control plots showed significantly higher moisture than cover crop plots at the end of the cover cropping season in all three years (a, b, c). The control's moisture advantage persisted at sorghum planting in year one (d), but not in year two or three (e, f). Year two showed higher moisture in the cover crop plots while year three showed no differences between the two. Years one and three (g, i) had significantly higher germination rates in the controls, while year two (h) showed no difference between cover crop and control germination.



ing. However, the sorghum germination rates showed significant differences between treatments. On average, controls had 6.70 seedlings m^{-1} and cover crops had 3.00 seedlings m^{-1} (t [73] = 4.52, $p < 0.001$; figure 2i). Germination was especially poor in the plots that had radish mixes during the cover cropping season. Control plots and plots with sunn hemp (*Crotalaria juncea* L.) during the cover crop season maintained adequate stands until major June rains overwhelmed the field with weeds and the farmer tilled the field to terminate.

Longer Recharge Periods May Reduce the Risk of Cover Cropping in Dry-Farmed Fields. The contrast between sorghum failure after cover cropping in year one and comparable sorghum yields in year two illustrate the importance of the recharge period between cover crop and cash crop. Until a field receives enough rainfall to recoup the moisture deficit incurred by cover crop evapotranspiration, plots without cover crops maintain a moisture advantage (Unger and Vigil 1998). Lengthening the window for such rainfall to occur helps improve the chances of a successful cash crop. However, even the 99-day recharge window of year three was insufficient when less than 30 mm of rain fell in small increments over that timeframe. A longer recharge period increases the probability that rain might fall, albeit unpredictably.

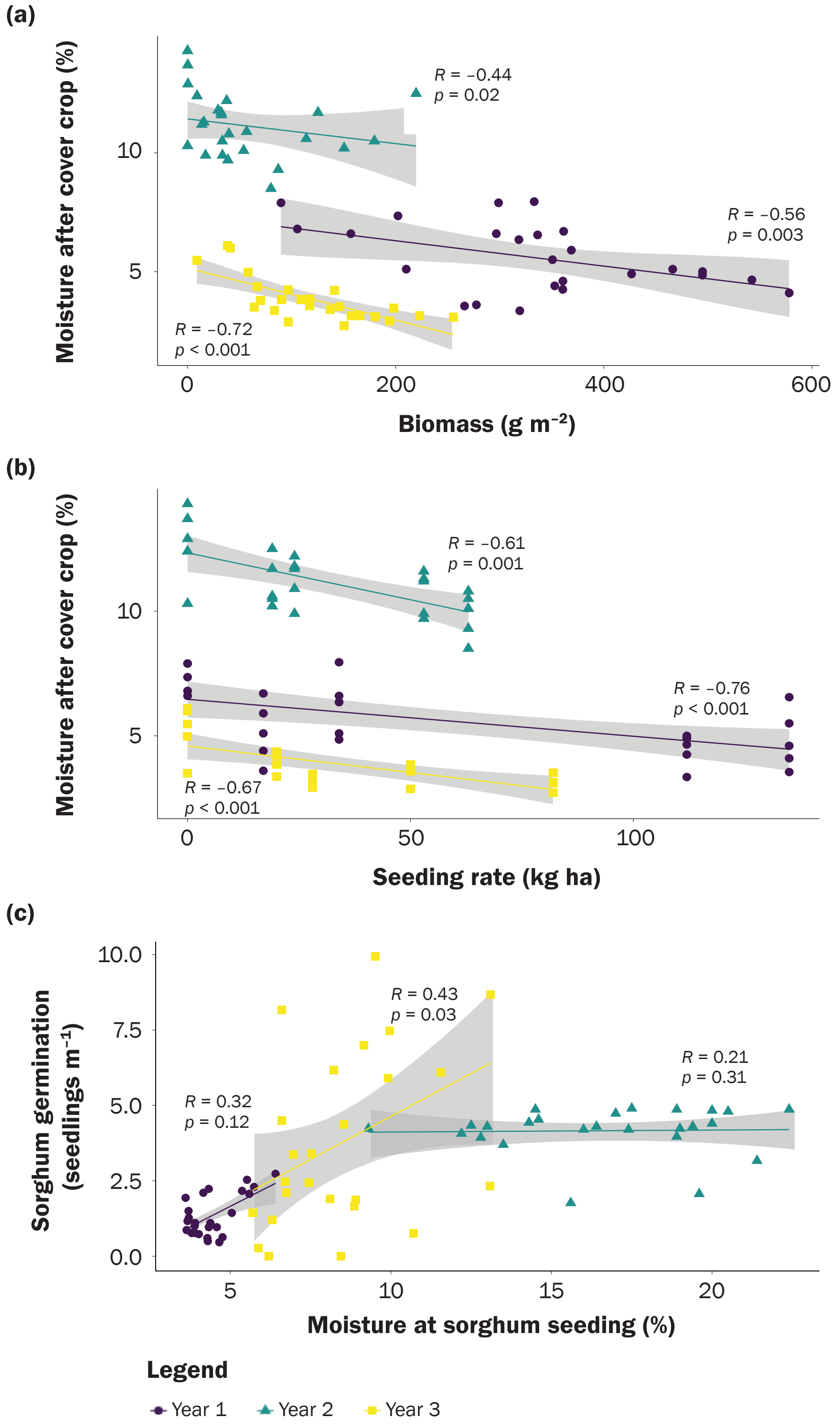
Higher Cover Crop Seeding Rate and Biomass Associated with Lower Soil Moisture. High biomass production is usually a desirable quality in cover crops because it facilitates key goals like weed suppression, soil organic matter accumulation, and increased microbial activity (Brennan and Boyd 2012). However, these strengths may come at the cost of increased moisture usage, a major liability in the context of dryland agriculture. Figure 3a shows the relationship between total plot biomass with soil moisture at the end of each cover cropping season. In each year, higher cover crop biomass led to lower soil moisture. The relationships are strongest in year one ($R = -0.56$, $p = 0.003$) and year three ($R = -0.72$, $p < 0.001$), the drier years in this study. More biomass means more evapotranspiration, lower soil moisture, and an increased risk of cash crop germination failure. Figure 3b shows the correlation between soil moisture at sorghum seeding and sorghum germination. These correlations are weaker overall, but the pattern remains that soil moisture impacted sorghum germination more strongly in drier years one ($R = 0.32$, $p = 0.12$) and three ($R = 0.43$, $p = 0.03$) than in wetter year two ($R = 0.21$, $p = 0.31$). This suggests that moisture was a limiting factor for germination in years one and three but not in year two.

Cover crop biomass is a product of both species selection and seeding rate. Figure 3c shows the negative correlation between seeding rates and soil moisture after cover cropping. Higher seeding rates were associated with lower soil moisture in all three seasons. Reducing seeding rates to the lowest viable level is another option for reducing cover crop moisture usage and managing the risk of cash crop failure. However, lower seeding rates and subsequently lower cover crop biomass will likely slow progress toward some of the goals that farmers seek from cover crops.

Cover crop species vary in their growth habits and water usage rates. Some cover crops like forage pea, triticale, and tillage radish (*Raphanus sativus*) leave soils with a greater soil moisture deficit than others like sunn hemp, clover (*Trifolium incarnatum*), and

Figure 3

Correlations among biomass, seeding rate, germination, and soil moisture. In each year, higher cover crop (a) biomass and higher cover crop (b) seeding rates were both associated with lower soil moisture levels. The negative relationship was stronger in the drier years (one and three) than in wetter year two. (c) Lower soil moisture at sorghum planting was correlated with lower sorghum germination. The relationship was again stronger in year one and three under dry conditions than in year two, when moisture was less limited.



vetch (*Vicia villosa*) (table 4 and figure 4). Further research could assess the water use efficiency for cover crop candidates to help pinpoint options that have best rates of biomass production at the lowest moisture cost.

Reduced Tillage Termination Methods May Improve Soil Moisture Retention. Although this study did not include a no-till or reduced till area for comparison, termination by tillage may enhance moisture loss by disturbing the soil and burying residue that might otherwise conserve soil moisture. As one farmer collaborator puts it, "you lose moisture to whatever depth you put steel in the ground." This problem could be alleviated by reduced or no-till termination methods, but options remain limited for organic farmers in the arid subtropics. Conventional growers can terminate with herbicides instead of tillage, while northern organic growers rely on winterkill at the end of their cover cropping seasons. Mechanical termination with roller crimpers has been suggested for organic growers, but trials show high risks of yield loss in subsequent crops (Mischler et al. 2010). South Texas can experience several consecutive winters without a freeze, making winterkill an unreliable termination strategy. Local attempts at no-till organic termination with roller-crimpers and flail mowers have resulted in untenable levels of cover crop regrowth. Effective no-till organic termination methods remain a major obstacle that could greatly improve the potential of cover cropping without irrigation in semiarid regions if resolved.

Summary and Conclusions

The trends over three seasons of winter cover cropping in semiarid south Texas reinforce the concerns of local area farmers and the reports from the literature that moisture management is a major obstacle to successful cover crop implementation in semiarid regions. These findings suggest that careful attention to cover crop species choice, seeding rates, termination method, and recharge period length can reduce the risk of cover crop associated moisture loss and impacts on subsequent cash crops. Although cover crops can provide tremendous benefits toward improved soil health and soil biology in south Texas (Soti et al. 2016; Soti and Racelis 2020), the value of these benefits must be considered carefully against the agronomic implications of soil moisture—the limiting factor of crop success among dryland farmers in semiarid regions. Over time, the benefits of cover cropping may gradually accrue to the point that they outweigh the associated direct and indirect costs (DeVincentis et al. 2020), but the high short-term costs, including risk of cash crop failure, may discourage many farmers from adopting these practices. Rehabilitating soil health is critical both for agricultural productivity and ecological health, but farmers in water-limited regions like the Rio Grande Valley of deep south Texas may require additional support. Payments for conservation practices as proposed by the current administration can help ease the initial burden of cover crops while long-term soil health gains accumulate (Bergtold et al. 2019; Democratic National Committee 2021).

Acknowledgements

Special thanks to Andy Cruz and Joseph Kim, our farm collaborators at Hilltop Gardens in Lyford, Texas, and to all the student researchers who helped collect and process this three-year data set including Mylen Arias, Alyssa Cano, Diana Cantu, Fallon Fraustro, Suzanne El-Haj, Allison Kaika, Matthew Kutugata, Habraham Lopez, Roberto Reyna Oviedo, Erika Salamanca, and Amrita Singh.

Declaration on Conflict of Interest

The Subtropical Soil Health Initiative is supported by the Conservation Innovation Grants program of the USDA Natural Resources Conservation Service (NRCS), under grant #69-3A75-17-281 with additional funding from an NRCS Soil Science Collaborative Research Grant.

References

Bergtold, J.S., S. Ramsey, L Maddy, and J.R. Williams. 2019. A review of economic considerations for cover crops as a conservation practice. Renewable Agriculture and Food Systems 34(1):62-76. https://doi.org/10.1017/S1742170517000278.

Berrada, A.F., and C. Roseberry. 2018. The feasibility of cover crops in dryland cropping systems in SW Colorado and SE Utah. Colorado State Agricultural Experiment Station Technical Bulletin 1. Fort Collins, CO: Colorado State University Extension. https://hdl.handle.net/10217/187709.

Brennan, E.B., and N.S. Boyd. 2012. Winter cover crop seeding rate and variety affects during eight years of organic vegetables: I. Cover crop biomass production. Agronomy Journal 104(3):684-698. https://doi.org/10.2134/agronj2011.0330.

Daryanto, S., B. Fu, L. Wang, P.A. Jacinthe, and W. Zhao. 2018. Quantitative synthesis on the ecosystem services of cover crops. Earth-Science Reviews 185:357-373. https://doi.org/10.1016/j.earscirev.2018.06.013.

Democratic National Committee. 2021. Biden-Harris Plan to Build Back Better in Rural America. https://joebiden.com/rural-plan/.

DeVincentis, A.J., S.S. Solis, E.M. Bruno, A. Leavitt, A. Gomes, S. Rice, and D. Zaccaria. 2020. Using cost-benefit analysis to understand adoption of winter cover cropping in California's specialty crop systems. Journal of Environmental Management 261:110205. https://doi.org/10.1016/j.jenvman.2020.110205.

Fageria, N.K., V.C. Baligar, and B.A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. Communications in Soil Science and

Table 4

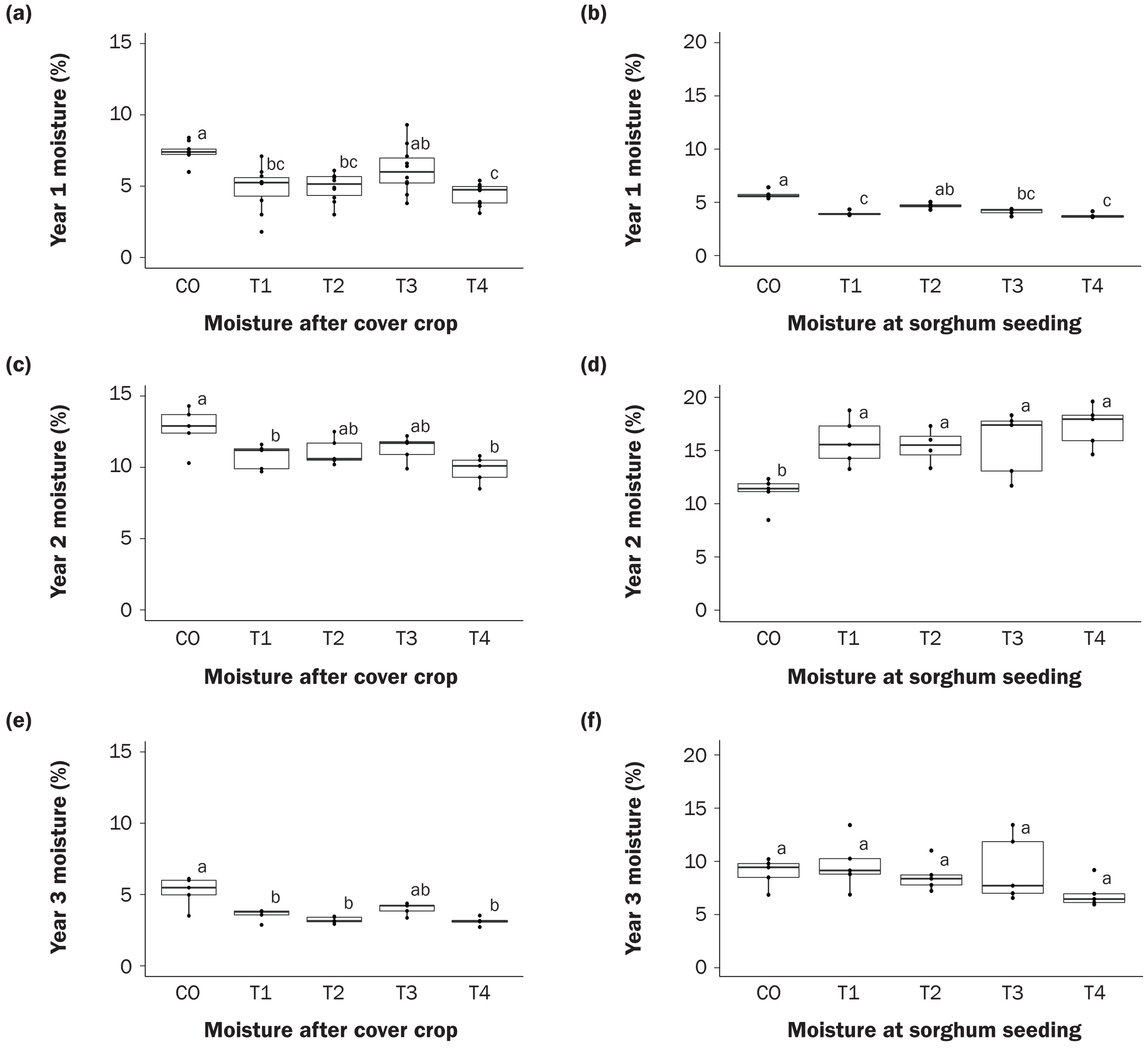
Cover crop moisture deficits.

		Cover crop – control moisture (%)	
Year	Treatment	Cover crop termination	Sorghum planting
1	Field pea/triticale (100#)	−2.88 ± 0.8	−1.97 ± 0.5
	Field pea (120#)	−2.45 ± 1.4	−1.77 ± 0.5
	Hairy vetch (15#)	−2.17 ± 1.2	−1.06 ± 0.5
	Crimson clover (15#)	−1.14 ± 1.3	−1.59 ± 0.4
2	Tillage radish/black oats (56#)	−2.88 ± 1.0	6.78 ± 1.6
	Cowpea/buckwheat/collard (48#)	−1.98 ± 1.1	5.20 ± 3.2
	Guar/proso millet/tillage radish (17#)	−1.62 ± 1.7	5.86 ± 3.1
	Sunn hemp/safflower/rapeseed (21#)	−1.42 ± 0.8	5.00 ± 4.3
3	Mustard/radish/cowpea/sunn hemp (77#)	−2.08 ± 1.2	−2.00 ± 1.6
	Tillage radish/hairy vetch/black oats (25#)	−2.00 ± 1.2	−0.33 ± 1.5
	Sunn hemp (45#)	−1.63 ± 1.1	0.73 ± 2.4
	Sunn hemp (18#)	−1.21 ± 1.4	0.35 ± 2.3

Note: Negative values indicate that lower moisture in cover crop than control while positive values show higher moisture in cover crop.

Figure 4

Impacts of multiple cover crop treatments on soil moisture. This figure shows the same data as figure 2 with the cover crop category divided into its four component treatments to offer more insight into differential water usage by different cover crop species. Treatments marked with the same letter do not significantly differ from each other. The control plots have the highest moisture in each season, significantly higher than many of the cover crop treatments. Particularly high moisture users include T4 in year one (forage pea + triticale), T4 in year two (tillage radish + black oats), and T2 and T4 in year three (both mixes including tillage radish).



Plant Analysis 36(19-20):2733-2757. https://doi.org/10.1080/00103620500303939.

Jian, J., X. Du, M.S. Reiter, and R.D. Stewart. 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biology and Biochemistry 143:107735.

Kaspar, T.C., and J.W. Singer. 2011. The use of cover crops to manage soil. *In* Soil Management: Building a Stable Base for Agriculture, ed. J.L. Hatfield and T.J. Sauer, 321-337. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2136/2011.soilmanagement.c21.

Lu, Y.C., K.B. Watkins, J.R. Teasdale, and A.A. Abdul-Baki. 2000. Cover crops in sustainable food production. Food Reviews International 16(2):121-157. https://doi.org/10.1081/FRI-100100285.

Mischler, R., S.W. Duiker, W.S. Curran, and D. Wilson. 2010. Hairy vetch management for no-till organic corn production. Agronomy Journal 102(1):355-362. https://doi.org/10.2134/agronj2009.0183.

Moran, P.J., and S.M. Greenberg. 2008. Winter cover crops and vinegar for early-season weed control in sustainable cotton. Journal of Sustainable Agriculture 32(3):483-506. https://doi.org/10.1080/10440040802257835.

Nielsen, D.C., D.J. Lyon, R.K. Higgins, G.W. Hergert, J.D. Holman, and M.F. Vigil. 2016. Cover crop effect on subsequent wheat yield in the Central Great Plains. Agronomy Journal 108:243-256. https://doi.org/10.2134/agronj2015.0372.

NOAA NCEI (National Oceanic and Atmospheric Administration-National Centers for Environmental Information). 2020. Data Tools: 1981-2010 Normals. https://www.ncdc.noaa.gov/cdo-web/datatools/normals.

Qi, Z., M.J. Helmers, and A.L. Kaleita. 2011. Soil water dynamics under various agricultural land covers on a subsurface drained field in north-central Iowa, USA. Agricultural Water Management 98(4):665-674. https://doi.org/10.1016/j.agwat.2010.11.004.

R Core Team. 2019. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Robinson, C., and D. Nielsen. 2015. The water conundrum of planting cover crops in the Great Plains: When is an inch not an inch? Crops and Soils 48(1):1-7. https://doi.org/10.2134/cs2015-48-1-7.

Sharma, V., and S. Irmak. 2017. Soil-water dynamics, evapotranspiration, and crop coefficients of cover-crop mixtures in seed maize cover-crop rotation fields. II: Grass-reference and alfalfa-reference single (normal) and basal crop coefficients. Journal of Irrigation and Drainage Engineering 143(9):04017033. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001214.

Shrestha, A., R. Cox, Y. Wu, O. Robles, L.L. deSouza, S.D. Wright, and J.A. Dahlberg. 2016. Moisture and salt tolerance of a forage and grain sorghum hybrid during germination and establishment. Journal of Crop Improvement 30:668-683. https://doi.org/10.1080/15427528.2016.1219895.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agronomy Journal 97:322-332. https://doi.org/10.2134/agronj2005.0322a.

Soti, P., and A. Racelis. 2020. Cover crops for weed suppression in organic vegetable systems in semiarid subtropical Texas. Organic Agriculture 10:429–436. https://doi.org/10.1007/s13165-020-00285-4.

Soti, P.G., S. Rugg, and A. Racelis. 2016. Potential of cover crops in promoting mycorrhizal diversity and soil quality in organic farms. The Journal of Agricultural Science 8(8):42. https://doi.org/10.5539/jas.v8n8p42.

Stewart, R.D., J. Jian, A.J. Gyawali, W.E. Thomason, B.D. Badgley, M.S. Reiter, and M.S. Strickland. 2018. What we talk about when we talk about soil health. Agricultural & Environmental Letters 3:180033. https://doi.org/10.2134/ael2018.06.0033.

Thomas, W., R.G. Ley, R. Stevens, R. Topielec, and W.H. Neibling. 1994. Soil water monitoring and measurement. Pullman, WA: Pacific Northwest Extension Publications. https://rex.libraries.wsu.edu/esploro/outputs/report/Soil-Water-Monitoring-and-Measurement/99900501862201842?institution=01ALLIANCE_WSU#file-0.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. Journal of Soil and Water Conservation 53(3):200-207.

USDA NASS (National Agricultural Statistics Service). 2017. County Profiles: Cameron, Hidalgo, Starr, and Willacy Counties, Texas. Washington, DC: USDA NASS.

USDA NRCS (Natural Resources Conservation Service). 2020. Web Soil Survey. Washington, DC: USDA NRCS. https://websoilsurvey.sc.egov.usda.gov/.

Yoder, L., M. Houser, A. Bruce, A. Sullivan, and J. Farmer. 2021. Are climate risks encouraging cover crop adoption among farmers in the southern Wabash River Basin? Land Use Policy 102:105268. https://doi.org/10.1016/j.landusepol.2020.105268.

Zibilske, L.M., and D.J. Makus. 2009. Black oat cover crop management effects on soil temperature and biological properties on a Mollisol in Texas, USA. Geoderma 149:379-385. https://doi.org/10.1016/j.geoderma.2009.01.001.