United States Department of Agriculture

FINAL STUDY REPORT March 2025
Lockeford Plant Materials Center
Lockeford, CA

Adaptation of Warm Season Cover Crops for California's Central Valley

Margaret Smither-Kopperl, Annie Edwards and Valerie Bullard

Figure 1. Warm season cover crop plots on 9/6/23, 54 days after planting. Millets are the 4 rows on the left with 2 rows of legumes on the right, lower growing plots are cowpeas, and the tall plots are sun hemp. Photo: Annie Edwards, CAPMC.

ABSTRACT

Warm season annual cover crops are not widely used in California as irrigation water is required for their establishment. However, their use can provide multiple benefits to cropping systems including increased infiltration, erosion reduction, weed suppression, nitrogen fixation and cycling, and improvements in soil health. The purpose of this study was to evaluate the adaptation of commercially available cultivars and varieties of seven annual warm season cover crop species to California's Central Valley at the Lockeford Plant Materials Center (CAPMC) in 2021, 2022 and 2023. Species evaluated were legumes cowpea (*Vigna unguiculata*) and sunn hemp (*Crotalaria juncea*) and five millets: Japanese millet (*Echinochloa esculenta)*, Proso millet (*Panicum milaceum*), hybrid pearl millet (*Pennisetum glaucum*), foxtail millet (*Setaria italica*) and browntop millet (*Urochloa ramosa*). Characteristics evaluated were germination rate, canopy cover, height, disease and insect resistance, 50% bloom date, aboveground biomass production, and forage quality. Total irrigation water applied during 2021, 2022, and 2023 was 4.8, 6.7, and 6.0 inches respectively, while total precipitation over the previous winter and spring was 10.0, 17.0, and 32.0 inches. As expected, plant height and biomass production increased from 2021 to 2023 in tandem with increased winter precipitation for all species. There were no significant differences between the three cowpea cultivars, Chinese Red, Iron & Clay and Red Ripper, while sunn hemp consistently produced the greatest height and dry matter in above ground biomass. Leafy 22 and Tifleaf 3 hybrid pearl millets had significantly more canopy cover than the other millets at 90 days after planting (DAP) and had the highest biomass production. All species are well adapted for growth in California's Central Valley as a warm season cover crop, with minimal irrigation required for establishment. Additional evaluation is needed to assess water use and water budgets of warm season cover crops in annual cropping systems.

Margaret Smither-Kopperl, Manager; Lockeford Plant Material Center, 21001 N. Elliott Rd., Lockeford, CA 95237, margaret.smither-kopperl@usda.gov.

INTRODUCTION

The incorporation of cover crops into cropping systems can provide multiple benefits including microbial changes with increased aggregation of soil particles (Brennan & Acosta-Martinez, 2017; Schaeffer et al., 2020), the reduction or prevention of soil erosion, increased infiltration from precipitation and irrigation events, and greater water holding capacity (Fageria, et al., 2005; Magdoff, F & H. Van Es., 2009). A recent report found, "consistent water-related benefits of cover cropping demonstrated in the California based research literature are increased infiltration of water into the soil (often ≥40%) and the reduction of runoff (often ≥40%)" (Sustainable Conservation, 2024). Nutrient cycling is enhanced when legumes are included. Additionally, other cover crop species sequester and cycle nitrogen reducing the amount of synthetic nitrogen fertilizer required for commodity crops and the subsequent nitrous oxide emissions and nitrate run-off to surface and ground water (Fageria et al., 2005; Magdoff, F &H. Van Es., 2009; Menegat et al., 2022). In addition, specific cover crops compete with weeds, break pest cycles, and provide habitat for pollinator species and beneficial insects, reducing the need for pesticide use within a following crop (Daryanto et al., 2018; Haring et al., 2023; Magdoff, F &H. Van Es., 2009). Cover crop use has been promoted for soil conservation since the Dust Bowl (USDA, 1936). Across the country it's use has increased from 10.2 million acres in 2012 to 15.3 million acres in 2017 (USDA, 2019). In California, it is estimated that about 5% of agricultural land is cover cropped; primarily over the winter rainy season with cool season cover crops (CDFA, 2020; Mitchell et al., 2017; Sustainable Conservation, 2024).

California's Mediterranean climate of hot, dry summers and cool, wet winters, requires irrigation for agricultural production. Irrigation requirements can be a significant barrier to the implementation of cover crops (Mitchell et al., 2017; Sustainable Conservation, 2024). The perception has been that cool season cover crops contribute to water loss through evapotranspiration (ET), and only recently has their contribution to the water cycle been understood (Mitchell et at., 2017; Sustainable Conservation, 2024). One challenge with unirrigated cool season cover crops is that germination in an unirrigated system will not occur until the onset of fall rains. Fall rains are becoming increasingly unpredictable, and if the first rains are heavy, erosion and loss of planted seed occurs. Another barrier to cool season cover crop use is the amount of biomass produced. Large amounts of biomass can interfere with commodity crop establishment in spring and early summer in annual cropping systems such as tomato and sweet corn (Grower comments).

The CAPMC installed warm season cover crops at its Central Valley location in 2016 to initially assess growth at different planting dates (Bullard, 2018). Over the years, grasses, legumes, and forbs were evaluated. Millets and cowpeas were consistently among the most robust species (Bullard & Smither-Kopperl, 2022). The purpose of this study, part of a larger regional study with the Tucson, AZ, and Fallon, NV Plant Materials Centers (PMC), was to conduct an evaluation of multiple species and varieties of millets, cowpeas, and sunnhemp as warm season cover crops for drought tolerance and adaptability to arid areas. The varieties selected for this study provide cover with living roots during fall rains to increase infiltration and reduce erosion. They also winterkill with cold temperatures so spring termination procedures are not necessary. This study is timed to coincide with use after row crops, with minimal irrigation. Forage information was also collected as there is potential for using the material for livestock grazing.

MATERIALS AND METHODS

This warm season cover crop trial took place over three years (2021 to 2023) at the CAPMC. The CAPMC is in the northeastern corner of the San Joaquin Valley in central California and sits on a historical flood plain on the west bank of the Mokelumne River. This trial was planted into a Vina fine sandy loam with 0-2 percent slopes. This soil series has deep, well-drained soils with a pH ranging from moderately acid to slightly alkaline, available water storage (AWS) is estimated as 7 inches (NRCS California eVeg guide, 2024, NRCS Web Soil Survey, 2025).

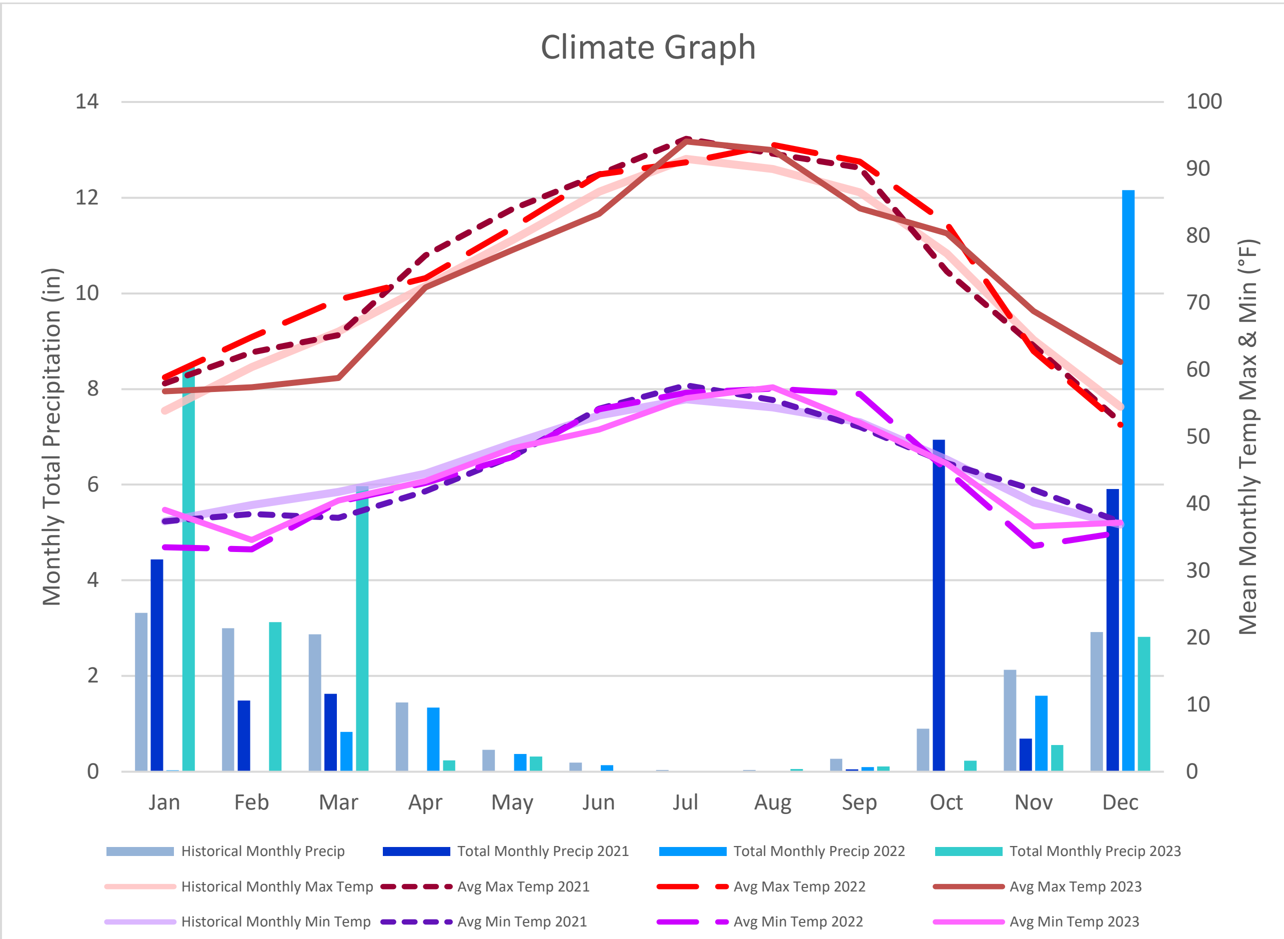

Figure 2. Monthly weather data from January through December was provided from Western Weather Group Lockeford Weather Station located directly across the river from the CAPMC. Average weather summaries from 1893-2015 for the Lodi area were provided from Western Regional Climate Center.

For the first two years of the study, California was in extreme drought (Figure 2). Water years are measured from June and in 2021, the previous water year had total rainfall of only 6 inches in the spring of 2021. The water year for 2022 was a total of 17 inches, but 15 inches was in the fall and winter of 2021 and only 2 inches during winter and spring of 2022. In the third year total rainfall was 32 inches, almost double the average for the site. The study was planted in Field 7 with a Great Plains cone seeder (Salina, KS) on 6/10/2021, 7/20/2022, and 7/19/2023. Each year the study was planted in a different area of Field 7, that had been left fallow the previous year. Site preparation included disking (x3), cultipacking, and pre-irrigation prior to planting. The trial layout was a randomized complete block design with four blocks running north to south, following the field site's slight slope and along a moisture gradient. Plot dimensions were 20 feet long x 5 feet wide with a planting spacing of 9 rows at 7 inch spacing. Irrigation was applied by a linear irrigation system, pre-irrigation amounts were 0.8 inches in 2021, and 4.3 and 3.0 inches for years 2022 and 2023. Through oversight, adequate pre-irrigation was not applied in 2021, leading to a greater requirement for irrigation after planting, with the potential for soil crust development. After seeding and germination, minimal irrigation was applied when the soil moisture was low and plants appeared drought stressed. Over the three years of the trial, additional irrigation applications totaled 4.0 (2021), 2.5 (2022) and 3.0 (2023) inches, applied early in the morning to reduce losses from evaporation.

Treatments included: three cowpea varieties, ‘Tropic’ sunn hemp, and five millet species. Seeding rates and depths were species dependent (Table 1).

Table 1. Species included in the 2021-2023 Lockeford Plant Materials Center warm season cover crop trial and their associated target seeding rates and seeding depths.

Common Name	Species Name	Cultivar/Variety	Target Seeding Rate (lbs/ac)	Seeding depth (in)
Cowpeas	*Vigna unguiculata*	Chinese Red	50	1 - 2
Cowpeas	*Vigna unguiculata*	Iron & Clay	50	1 - 2
Cowpeas	*Vigna unguiculata*	Red Ripper	50	1 - 2
Sunn Hemp	*Crotalaria juncea*	‘Tropic Sun’	45	1
Japanese Millet	*Echinochloa esculenta*	VNS*	20	0.25 - 0.5
Proso Millet	*Panicum miliaceum*	Horizon	20	0.5 - 0.75
Proso Millet	*Panicum miliaceum*	Dove	20	0.5 - 0.75
Hybrid Pearl Millet	*Pennisetum glaucum*	Leafy 22	20	0.5 - 0.75
Hybrid Pearl Millet	*Pennisetum glaucum*	Tifleaf 3	20	0.5 - 0.75
Foxtail Millet	*Setaria italica*	White Wonder	20	0.25 - 0.5
Foxtail Millet	*Setaria italica*	German	20	0.25 - 0.5
Browntop Millet	*Urochloa ramosa*	VNS	20	0.5 - 1

*VNS= Variety not stated

Evaluations were continuous throughout the growing seasons. Germination and field emergence, defined as how well a species germinates and emerges in the field after planting, were recorded at 7, 14, 21, & 28 DAP (days after planting) using 1-5 scale, where 1 = poor (0-20% germination), 2= fair (21-40% germination), 3= good (41-60% germination), 4 = very good (61-80% germination), and 5 = excellent (81-100% germination). Canopy cover photos were taken 30, 60, and 90 DAP and the software Foliage from Canopeo (canopeoapp.com) was used to estimate percent cover.

At 50% bloom, photos, disease and insect resistance ratings, height, and fresh weight aboveground biomass (FWAB) were collected. Disease and insect resistance, a visual estimate of the plant’s resistance to foliar diseases and insect damage, was recorded using 0 – 4 scale, where 0 = no damage (0% damage), 1 = some (1-25% damage), 2 = moderate (26-50% damage), 3 = bad (51-75% damage), and 4 = severe (76-100% damage). Plant height (in) is the average height of the canopy measured from the base to the tallest point at three representative locations per plot. FWAB was defined as the above-ground accumulation of plant growth. For this procedure, biomass was collected as close to the ground as possible, leaving no more than ¼ inch stubble height. Locations for samples were selected by randomly placing a square foot quadrat in the plot and collecting the aboveground biomass that fell within the square foot perimeter. Weeds were excluded. After weighing and recording the FWAB, the samples were dried in a drying oven until their weights stabilized. The stabilized dry weight was recorded as dry matter weight (DM). Forage quality was collected from a composite sample of each treatment's DM and sent to Sierra Testing Services (Dog Town, CA) for nutrient analysis testing. Analysis included crude protein, percent nitrogen content, and true digestibility. Only one sample per treatment was sent for forage quality testing. Weather data was recorded, and irrigation applications were tracked throughout the trial.

Statistical analysis was completed on all three years of trial evaluations using Statistix 10 (Analytical Software, Tallahassee, FL). Ordinal data (germination, disease, and insect resistance) was analyzed using Kruskal-Wallis one-way analysis of variance (AOV) and Dunn's All-Pairwise Comparisons Test to separate means at the 5% level. Analysis was done on quantitative plant measurements (plant height, FWAB, DM, and canopy cover) using the analysis of variance (AOV) procedure for a randomized complete block design (RCBD) along with Tukey's 1 Degree of Freedom test for non-additivity. Significant means were separated with Tukey's Honestly Significant Difference (HSD) All-Pairwise Comparisons Test at the 5% level.

RESULTS AND DISCUSSION

Legumes

Germination and emergence of sunn hemp was similar over all three years, while the cowpea variety Red Ripper had slightly lower germination during 2021 (Table 2).

Table 2. Average legume germination results 7, 14, 21, and 28 days after planting the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Treatment	**Variety/ Cultivar**	**Year and Days after Planting**											
		2021				**2022**				**2023**			
		7	**14**	**21**	**28**	**7**	**14**	**21**	**28**	**7**	**14**	**21**	**28**
Cowpea	Chinese Red	3.5	4.3	4.3	5.0	3.8	5.0	5.0	5.0	3.3	4.3	4.5	4.8
Cowpea	Iron & Clay	2.5	4.3	4.5	4.8	3.5	5.0	5.0	5.0	3.5	4.0	5.0	5.0
Cowpea	Red Ripper	2.3	3.8	3.8	3.8	3.0	4.8	5.0	5.0	2.8	4.0	5.0	5.0
Sunn hemp	Tropic Sun	3.3	4.5	5.0	5.0	3.5	5	5.0	5.0	2.8	4.0	5.0	5.0

Germination was recorded at 7, 14, 21, & 28 DAP (days after planting) using 1-5 scale, where 1 = poor (0-20% germination), 2= fair (21-40% germination), 3= good (41-60% germination), 4 = very good (61-80% germination), and 5 = excellent (81-100% germination).

Table 3. Legume canopy cover 30, 60 and 90 days after planting in the warm season cover crop trial at Lockeford, CA Plant Materials Center, 2021-2023.

Treatment	**Variety/ Cultivar**	**Years and Days after planting**								
		2021			**2022**			**2023**		
		30	60	90	30	60	90	30	60	90
Cowpea	Chinese Red	4.9[1] b[2]	12.7 ab	53.9 a	15.5 a	23.8 a	38.8 a	48.9 b	56.1 a	45.6 a
Cowpea	Iron & Clay	7.1 b	9 ab	40.2 a	17.8 a	12 a	17 a	52.1 ab	66.1 a	53.4 a
Cowpea	Red Ripper	3.7 b	5.7 b	36.4 a	15.3 a	10.5 a	20.5 a	77.9 a	68.3 a	53.4 a
Sunn hemp	Tropic Sun	15.1 a	22.4 a	37.6 a	28 a	37.8 s	22.5 a	70.1 ab	73.7 a	35.2 a

[2]*Means in columns followed by the same letters are not significantly different at P<0.05.*

Legume canopy cover results varied from year to year (Table 3). Predictably, cover was lower in the drought years of 2021 and 2022 versus the high rainfall year of 2023. The shiny cowpea leaves may have resulted in an underestimate of cover by the Foliage application (Canopeo).

The 50% bloom date data was recorded in 2022 and 2023 (Table 4). Sunn hemp had the same maturation date for both years. Chinese Red and Red Ripper cowpeas matured earlier in 2023 compared to 2022, while the reverse was true for Iron and Clay, which took 20 days longer to reach the 50% bloom stage. This could reflect different water usage and an extended period of vegetative growth for Iron &Clay during a precipitation year.

Table 4. Days after planting to 50% bloom and average plant height of legumes in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Plant	Cultivar	50% Bloom DAP[1]			Height (inches)		
		2022	2023		2021	2022	2023
Cowpea	Chinese Red	76	69		13 b[2]	14.8 b	17.3 b
Cowpea	Iron & Clay	83	103		12.5 b	14.5 b	35.8 b
Cowpea	Red Ripper	76	71		9.5 b	10.8 b	16.5 b
Sunn hemp	Tropic Sun	83	83		25.3 a	40.5 a	75.3 a

. [2]*Means in columns followed by the same letters are not significantly different at P<0.05.*

There was no significant difference in height between the cowpea cultivars (Table 4). However, Iron & Clay, which includes vining and erect characteristics, was almost twice as tall as Chinese Red and Red Ripper in 2023. Sunn hemp is an erect species, rather than vining, and was significantly taller compared to the cowpea cultivars in all three years. Height increased over the three years of the study for all entries likely due to increasing precipitation totals over the previous winter and spring.

Table 5. Biomass production of legumes in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Plant	Cultivar	Fresh Weight Above Ground (ton/acre)			Dry weight (ton/acre)		
		2021[1]	2022	2023	2021	2022	2023
Cowpea	Chinese Red	7.4 a	21.5 a	32.7 a	1.3 a	3.2 a	5.8 a
Cowpea	Iron & Clay	6.4 a	15.1 ab	23.4 a	1.3 a	2.7 a	5.9 a
Cowpea	Red Ripper	6.1 a	17.4 ab	45.7 a	1.2 a	2.4 a	6.8 a
Sunn hemp	Tropic Sun	5.3 a	9.4 b	34.2 a	1.7 a	2.9 a	10.5 a

[1] *Collection of biomass at 90DAP in 2021 and 50% bloom in 2022 and 2023.* [2]*Means in columns followed by the same letters are not significantly different at P<0.05.*

For all legumes, biomass increased each year of the study (Figures 3 and 4). Within years there were no significant differences in yield for legumes, apart from 2022, when the fresh weight of sunn hemp was lower than the Chinese Red cowpea (Table 5). Dry weight biomass was not significantly different between legumes in any year (Table 5). Sunn hemp had the highest dry matter production of any legume in 2023, although the fresh weight of red ripper surpassed it.

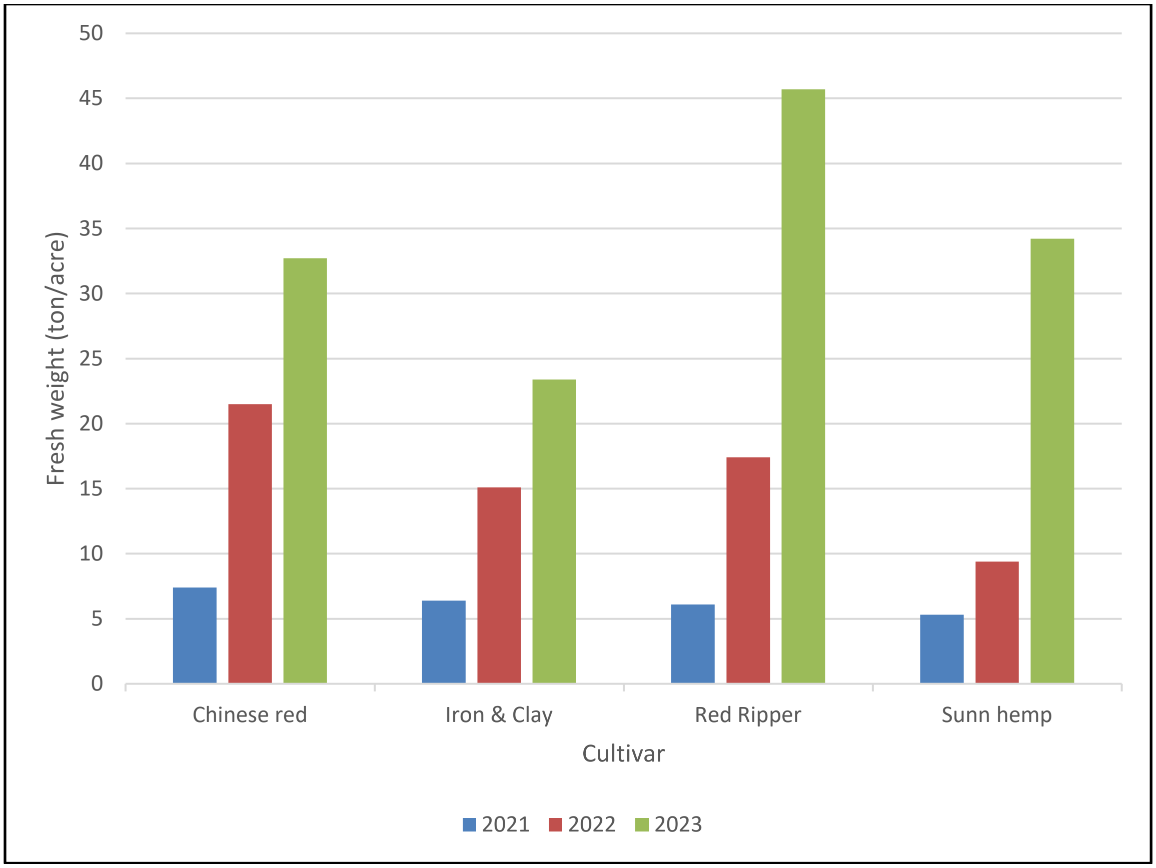

Figure 3. Biomass production of legumes (fresh weight) in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

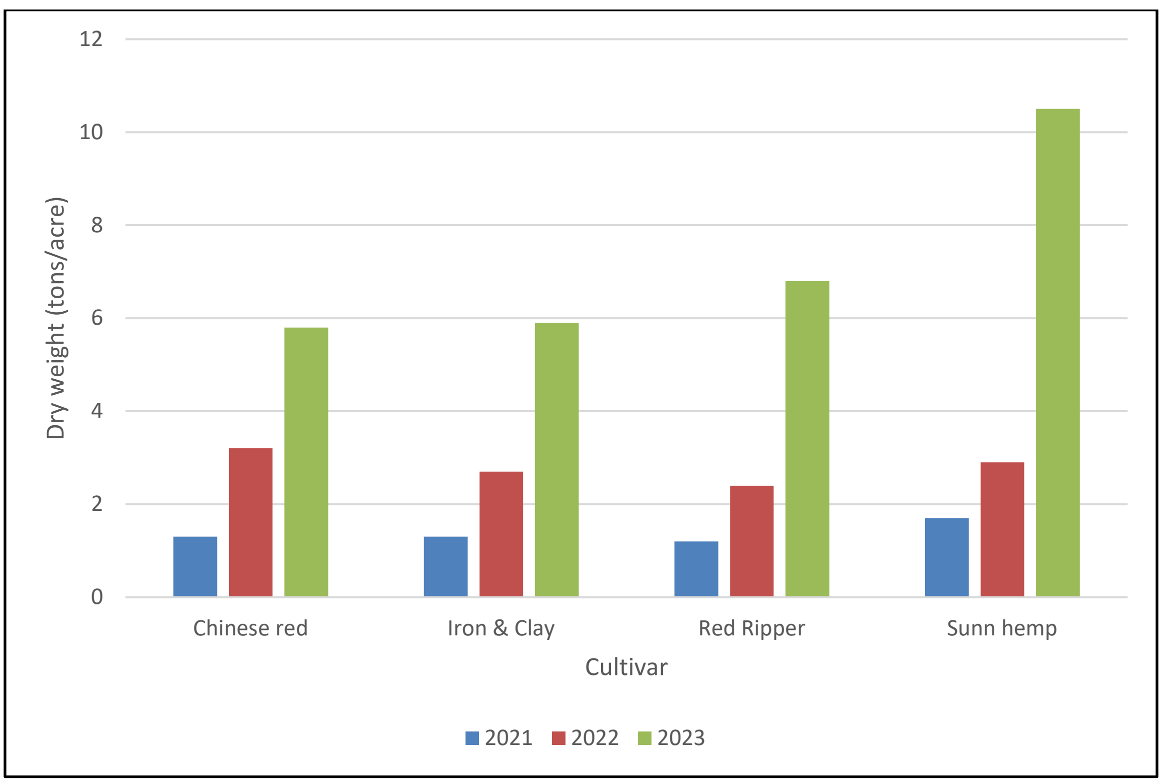

Figure 4. Biomass production of legumes (dry weight) in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Disease and insect incidences were low for all legumes, in all years, with scores of less than 25% damage for both categories (Table 6, Figures 5-8).

Table 6. Insect and disease incidences of legumes in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Plant	**Cultivar**	**Insect Resistance**			**Disease Resistance**		
		2021	**2022**	**2023**	**2021**	**2022**	**2023**
Cowpea	Chinese Red	1	1	0.5	1	0.25	0
Cowpea	Iron & Clay	2	1	0.5	1.75	0.25	0
Cowpea	Red Ripper	1.25	0.5	0	1	1.25	0
Sunn hemp	Tropic Sun	0.5	0.5	1.5	0	0.25	0.25

Insect and disease resistance was scored on a 0-4 scale, where 0 = no damage (0% damage), 1 = some (1-25% damage), 2 = moderate (26-50% damage), 3 = bad (51-75% damage), and 4 = severe (76-100% damage).

Figure 5 Cowpea, Chinese Red

Figure 6. Cowpea, Iron & Clay

Figure 7. Cowpea, Red Ripper

Figure 8. 'Tropic Sun' sunnhemp

Millets

Germination and emergence of all millets was higher in 2021 than the following 2 years (Table 7). The lowest ratings at 28 days were 3.5 for German foxtail millet in 2022 and browntop millet in 2023.

Table 7. Average millet germination results 7, 14, 21, and 28 days after planting the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Plant	**Cultivar**	**Year/Days after Planting (DAP)**											
		2021				**2022**				**2023**			
		7	**14**	**21**	**28**	**7**	**14**	**21**	**28**	**7**	**14**	**21**	**28**
Japanese Millet	VNS	2	4.25	5	5	2.25	3.75	4	4.25	1	2	3.75	4
Proso Millet	Horizon	2.5	4.25	4.75	5	4	4.5	4.5	4.5	3.75	2.75	4	4.5
Proso Millet	Dove	2.25	4.5	5	5	3	4	4.25	4.75	2.25	2.5	3.5	4.25
Hybrid Pearl	Leafy 22	3	5	5	5	3	4.5	4.75	5	3	3.5	3.75	4.75
Hybrid Pearl	Tifleaf 3	3.5	4.75	5	5	2.25	3.75	3.75	4.5	3.75	3	4.25	4.5
Foxtail	White Wonder	2	4.25	4.5	5	3	3.5	3.75	4.5	1.5	2.25	3.75	4.25
Foxtail	German	3.25	4.5	5	5	2	2.5	3	3.5	2.25	2.25	2.75	3.75
Browntop	VNS	2	4.5	5	5	2.25	1.75	3	4.25	1.5	1.5	2.25	3.5

Germination was recorded at 7, 14, 21, & 28 DAP (days after planting) using 1-5 scale, where 1 = poor (0-20% germination), 2= fair (21-40% germination), 3= good (41-60% germination), 4 = very good (61-80% germination), and 5 = excellent (81-100% germination).

There were no significant differences in canopy cover between the cultivars for the 30 and 60 DAP canopy cover readings (Table 8) except for Horizon proso millet at 60 days in 2023. The reduction in canopy cover readings at 90 days was due to early maturation of some cultivars, such as Horizon Proso millet in all three years (Figures 9-11). The hybrid pearl millets, Leafy 22 and Tifleaf 3, had significantly more canopy cover than the other millets at 90 DAP in 2023.

Figure 9. Proso millet, Horizon at 30 DAP.

Figure 10. Proso millet, Horizon at 60 DAP.

Figure 11. Proso Millet, Horizon at 90 DA

Table 8. Millet canopy cover 30, 60 and 90 days after planting in the warm season cover crop trial at Lockeford, CA Plant Materials Center, 2021-2023.

Millet	Cultivar	Year and Days after Plantings								
		2021			2022			2023		
		30	60	90	30	60	90	30	60	90
Japanese		32 a	43 a	24 ab	57 a	32 a	2 b	76 a	79 ab	5 c
Proso	Horizon	31 a	65 a	16 b	45 a	16 a	0.5 b	70 a	56 b	3 c
Proso	Dove	26 a	59 a	45 ab	50 a	52 a	12 b	77 a	86 a	6 c
Hybrid Pearl	Leafy 22	17 a	68 a	51 a	34 a	46 a	18 ab	74 a	85 a	59 a
Hybrid Pearl	Tifleaf 3	17 a	49 a	54 a	42 a	60 a	40 a	78 a	74 ab	72 a
Foxtail	White Wonder	35 a	52 a	38 ab	45 a	39 a	10 b	75 a	85 a	39 b
Foxtail	German	36 a	60 a	40 ab	54 a	56 a	20 ab	69 a	75 ab	36b
Browntop		24 a	53 a	33 ab	54 a	47 a	17 ab	61 a	87 a	18 c

[1]*Data recorded with Canopeo.* [2]*Means in columns followed by the same letters are not significantly different at P<0.05.*

The 50% bloom date data was recorded in 2022 and 2023, although the 2022 data, apart from the proso millets, is so similar that it appears not reliable (Table 9). Assessing pollination time in grasses can be challenging. In 2023, Horizon matured the earliest and the hybrid pearl millets, Leafy 22 and Tifleaf 3 the latest.

Table 9. Days after planting to 50% bloom and average plant height of millets in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Millet	Cultivar	50% Bloom DAP			Height (inches)		
		2022	2023		2021	2022	2023
Japanese		91	64		14.8 ab	19.3 ab	42 b
Proso	Horizon	40	48		17.5 a	17.5 ab	32.3c
Proso	Dove	71	65		17.5 a	24.3 a	56.8 a
Hybrid Pearl	Leafy 22	91	78		16 a	21.5 ab	31.3 c
Hybrid Pearl	Tifleaf 3	91	83		13 ab	22.8 a	43.3 b
Foxtail	White Wonder	91	62		15.3 a	22.5 a	42.8 b
Foxtail	German	91	63		14.3 ab	22.8 a	48 b
Browntop		91	62		9.5 b	16 b	31.3c

[1]*Days after planting.* [2]*Means in columns followed by the same letters are not significantly different at P<0.05.*

The height of browntop millet was significantly shorter than the other millets in all 3 years of the trial (Table 9, Figure 12). In 2023, Horizon and hybrid pearl were also the shortest and not significantly different than the browntop millet. Dove proso millet was significantly taller than the other millets in 2023, but not in the other years.

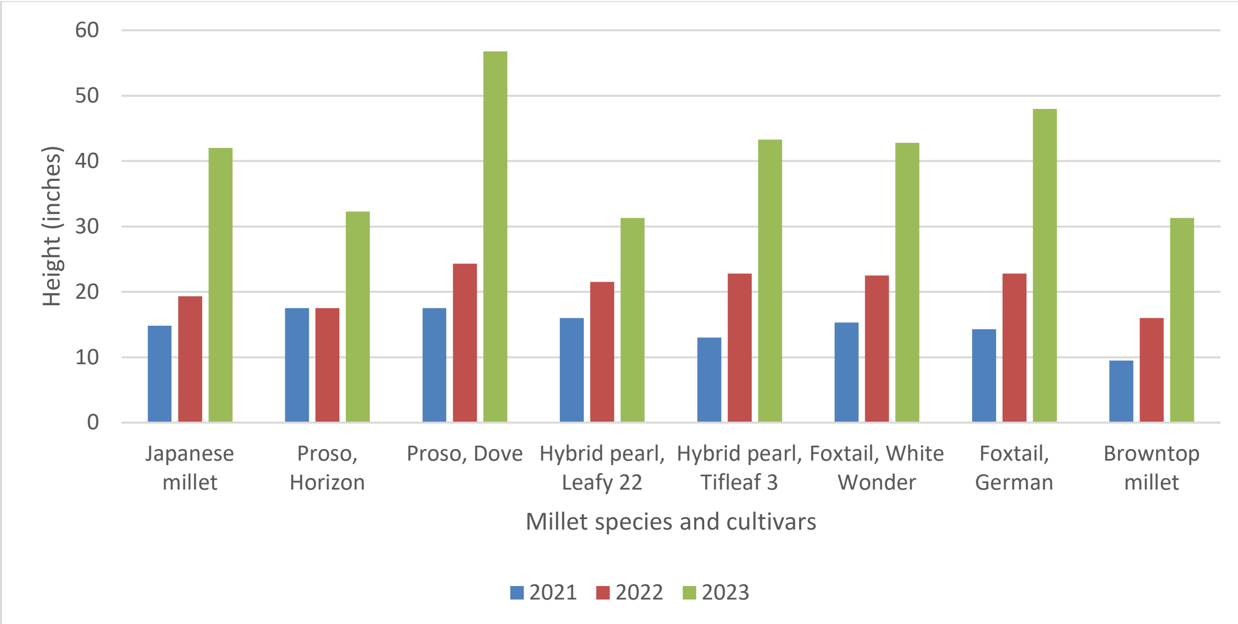

Figure 12, Plant height of millet species and cultivars.in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Biomass for all millets increased over the three summers of the study, in tandem with increased precipitation over the winter (Table 10, Figures 2, 13 and 14). There were no significant differences in yield for millets within years apart from 2021 & 2023, when Hybrid Tifleaf 3 had significantly higher biomass than Japanese millet (FWAB) and 'White' proso millet (FWAB & dry matter).
The two hybrid pearl millets, Leafy 22 and Tifleaf 3, produced the largest amount of fresh weight biomass in all three years of the study. Similarly, the largest amount of dry matter produced in 2023 was from the two hybrid pearl millets, plus Dove proso millet and German foxtail millet. The millets with the most consistent biomass production over the study were proso millet, Horizon and browntop millet.

Table 10. Biomass production of millets in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Species	Cultivar	FWAB ton/acre			Dry Matter lbs/acre		
		2021[1]	2022	2023	2021	2022	2023
Japanese		3.7 b[2]	8.5 a	19 ab	1.3 a	2.5 a	4.8 ab
Proso Millet	White	6.3 ab	4.1 a	14.0 b	2.3 a	2.3 a	2.8 b
Proso Millet	Dove	5.0 ab	9.5 a	31.4 ab	1.9 a	2.9 a	7.3 ab
Hybrid Pearl	Leafy 22	10 ab	18.5 a	33.4 ab	2.9 a	4.7 a	7.0 ab
Hybrid Pearl t	Tifleaf 3	10.5 a	15.3 a	40.1 a	2.9 a	3.8 a	8.5 a
Foxtail	White Wonder	5.7 ab	8.7 a	27.5 ab	2.2 a	3.7 a	6.0 ab
Foxtail	German	4.8 ab	7.9 a	29.7 ab	1.8 a	3.4 a	6.9 ab
Browntop		8.6 ab	6.4 a	19.1 ab	3.6 a	4.7 a	4.8 ab

[1] Collection of biomass at 90DAP in 2021 and 50% bloom in 2022 and 2023. [2]Means in columns followed by the same letters are not significantly different at P<0.05.

Disease and insect incidence was at low levels throughout, with scores of less than 25% damage for both categories (Table 11, Figures 15-23).

Table 11. Insect and disease incidences in millets in the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Species	**Cultivar**	Insect Resistance			Disease Resistance		
		2021	**2022**	**2023**	**2021**	**2022**	**2023**
Japanese		0.5	0	0	0	1.25	0
Proso Millet	White	0.25	0	1	0	0	0
Proso Millet	Dove	0	0	0.25	0	0	0.5
Hybrid Pearl	Leafy 22	0.25	0	0.5	0	0	0.25
Hybrid Pearl t	Tifleaf 3	1.25	1	0.25	0	0.25	0.5
Foxtail	White Wonder	0.75	0	0	0	0.5	0
Foxtail	German	0.25	0	0.5	0	0.75	0
Browntop		0	0	1	0	0.75	0.5

Insect and disease resistance was scored on a 0-4 scale, where 0 = no damage (0% damage), 1 = some (1-25% damage), 2 = moderate (26-50% damage), 3 = bad (51-75% damage), and 4 = severe (76-100% damage).

Figure 13. Japanese millet

Figure 15. Proso millet, Dove.

Figure 14. Proso millet, Horizon

Figure 16. Hybrid pearl millet, Leafy 22.


Figure 17. Hybrid pearl millet, Tifleaf 3.


Figure 18. Foxtail millet, German


Figure 19 Foxtail millet, White Wonder


Figure 20. Browntop millet

Forage Analysis

Data for forage analysis were collected annually, at 90 days in 2021 and 50% bloom in 2022 and 2023 (Table 12). For all species, as biomass increased in 2023, there was a reduction in crude protein compared to the previous years. Values over 20% are considered good and these were only attained for cowpeas during the drought years (George, 2001). Nitrate levels, only taken in 2023, were below <300 ppm, for all legumes and millets, and enough to be considered safe for livestock (Gupta, 2018). However, in 2022, the cowpeas, hybrid pearl millet and White Wonder foxtail millet exceeded this value for nitrates, indicating that care might be needed in timing for grazing forage in a dry year.

Correlation of Growth with Precipitation over the Previous Winter

The marked increase of growth for all species and cultivars over the three years of the study was not related to irrigation water applied. The only obvious cause was the increase in precipitation over the previous winter. This situation at the CAPMC will likely be different from other locations as the fine sandy loam soils are deep and have excellent water holding capacity. Effective cover cropping is always site specific, and another location, with poorer soils might not show the effect of additional water over the previous season.

Table 12. Forage analysis results from the warm season cover crop trial at the Lockeford, CA Plant Materials Center, 2021-2023.

Common Name	**Cultivar**	**Neutral Detergent Fiber (NDF) %**			**Acid Detergent Fiber (ADF) %**			**Crude Protein (CP) %**			**Nitrates (ppm)**	
Legume		**2021**[1]	**2022**[2]	**2023**[2]	**2021**	**2022**	**2023**	**2021**	**2022**	**2023**	**2022**	**2023**
Cowpeas	Chinese Red	21.1	24.2	31.6	22.9	24	29.3	27	17.7	14.9	550	<300
Cowpeas	Iron & Clay	28.1	29.2	41.2	25.7	27.6	37.2	26.8	17.5	11.3	494	< 300
Cowpeas	Red Ripper	24.4	25.5	38.1	24.5	24.9	33.4	28.5	21.2	17	521	< 300
Sunn Hemp	Tropic Sun	36.2	51.5	62.67	30.9	38.9	50.1	25.1	15.35	11.8	< 300	< 300
Millets												
Japanese Millet	VNS	48.3	47.3	57.4	27.3	29.1	38	20.1	13.3	9.9	< 300	< 300
Proso Millet	White	41.4	48.3	50.5	24.9	32.1	31	16.8	11.6	15.1	< 300	< 300
Proso Millet	Dove	43.5	50.1	57.9	23.7	30.5	40.1	19.6	13.4	8.4	< 300	< 300
Hybrid Pearlt	Leafy 22	47.2	48.5	58.4	28.4	31	38.4	16.3	12.9	8	497	< 300
Hybrid Pearl	Tifleaf 3	50.5	48.9	58.3	28.2	31	36.6	16.1	15.9	8.4	687	< 300
Foxtail Millet	White Wonder	50.1	51	64.5	29	31.9	43.2	16	11.6	9.2	497	< 300
Foxtail Millet	German	49.7	55	61.4	29.5	35.4	41.1	16.4	8.6	9.7	< 300	< 300
Browntop Millet	VNS	44.9	51.8	56.6	26.9	31.7	36.7	18.7	10.5	9.8	< 300	< 300

[1] Collection of biomass at 90DAP in 2021 and 50% bloom in 2022 and 2023.

CONCLUSION

All warm season species and varieties evaluated in this trial perform well in California's Central Valley and can be incorporated into a cover cropping system. Cover crops allow rainfall infiltration and prevent erosion with the first fall rains, while allowing early entry into the fields in late winter or early spring. Additional evaluation is needed to assess water use and water budgets in annual cropping systems in the Central Valley.

LITERATURE CITED

Analytical Software. (2013). Statistix 10 [Software], Tallahassee, FL.

Brennan, E. B., and V. Acosta-Martinez. 2017. Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production. Soil Biology and Biochemistry. 109: 188-204.

Bullard, V. 2018. Case Study: Maturation dates of Warm Season Cover Crop Species-2017, CAPMC. https://efotg.sc.egov.usda.gov/references/public/CA/CaseStudyMaturationDates_WarmSeasonCC_11-18.pdf

Bullard V. & M. Smither-Kopperl, 2021. Adaptation of Warm Season Cover Crops for California. USDA-NRCS. 21 pp. https://www.nrcs.usda.gov/plantmaterials/capmcsr13844.pdf .

CDFA - California Department of Food and Agriculture. California Agricultural Statistics Review 2019-2020. (https://www.cdfa.ca.gov/Statistics/PDFs/2020_Ag_Stats_Review.pdf. Accessed 6/15/2021)

Daryanto, S., B. Fu, L. Want, P. Jacinthe, & W. Zhao 2018. Quantitative synthesis on the ecosystem services of cover crops. *Earth-Science Reviews*, *185*, 357-373.

Fageria, N.K., V.C. Baligar, , & B.A. Bailey 2005. Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analysis*, *36*(19-20), 2733-2757.

George, M. (2001). *Annual Rangeland Forage Quality*. University of California Agriculture and Natural Resources. https://anrcatalog.ucanr.edu/pdf/8022.pdf

Gupta, R. 2018. Nitrate and Nitrite Accumulating Plants. Veterinary Toxicology, 3rd Edition (941-946). Academic Press.

Haring S, A.C.M. Gaudin, B.D. Hanson. 2023. Functionally diverse cover crops support ecological weed management in orchard cropping systems. *Renewable Agriculture and Food Systems*. 2023;38: e54. doi:10.1017/S1742170523000492

Magdoff, F., & H. Van Es, 2009.. *Building soils for better crops: sustainable soil management*. Sustainable Agriculture Research & Education (SARE).

Menegat, S., A. Ledo & R. Tirado. 2022. Greenhouse gas emissions from global production and use of synthetic nitrogen fertilizers in agriculture. Scientific Reports (Nature Publisher Group). 12(1). https://www.proquest.com/scholarly-journals/greenhouse-gas-emissions-global-production-use/docview/2706500365/se-2. doi: https://doi.org/10.1038/s41598-022-18773-w.

Mitchell, J.P., A. Shrestha, K. Mathesius, K.M. Scow, R.J. Southard, R.L. Haney, R. Schmidt, D. S. Munk, W.R. Horwath. 2017. Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA, Soil and Tillage Research 165:325-335. https://doi.org/10.1016/j.still.2016.09.001

NRCS eVeg Guide (2024). www/calflora.org/nrcs/index. NRCS eVegGuide 5

NRCS Web Soil Survey, 2025. https://websoilsurvey.nrcs.usda.gov/app/

Sustainable Conservation (2024) Cover cropping in the SGMA era: A comprehensive overview of the water impacts, policy implications, and recommendations for California's water managers. https://suscon.org/wp-content/uploads/2024/05/SC-Cover-Crop-SGMA-Report.pdf 89 pages

USDA. 1936. Cover Crops for Soil Conservation, Farmer's bulletin No. 1758. United States Department of Agriculture.

USDA. 2019. Agricultural Resources and Environmental Indicators, 2019. Economic Research Service. www.ers.usda.gov/webdocs/publications/93026/eib-208.pdf?v=7373.3