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RESEARCH ARTICLE

Evaluation of sunn hemp performance and nutritive value in Maine, USA

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Abstract

Background: Sunn hemp (*Crotalaria juncea* L. and *Crotalaria ochroleuca* G. Don) was evaluated as a warm-season legume to mitigate the "summer slump" in Maine's forage production caused by heat and moisture deficit stress.

Methods: This study compared three cultivars: "Crescent Sunn," "Loei," and "Red Mini," at 60 and 90 days after seeding over the 2024 and 2025 growing seasons to measure biomass, nitrogen (N) fixation, and nutritive value.

Results: Environmental conditions significantly impacted performance; biomass accumulation in 2024 was 4296 kg dry matter (DM) ha^{-1}, whereas the drought-stressed 2025 season produced 1099 kg DM ha^{-1}. Notably, drought increased the percentage of N derived from the atmosphere (52% in 2025 vs. 33.8% in 2024) and improved forage nutritive value by increasing crude protein and digestibility. Crescent Sunn and Loei consistently outperformed Red Mini; across all cultivars, delaying harvest to 90 days increased total biomass but elevated lignin levels and reduced digestibility.

Conclusions: Sunn hemp is a resilient forage and N source for northern temperate regions; management should target a 60-day harvest for high-quality animal feed or a 90-day harvest for maximum cover crop biomass.

KEYWORDS

drought, Maine, nitrogen fixation, nutritive value, sunn hemp

INTRODUCTION

In northern temperate regions, forage production faces a major mid-summer challenge called the "summer slump." During this time, the growth of traditional cool-season grasses and legumes, like timothy (*Phleum pratense* L.) or white clover (*Trifolium pratense* L.), is reduced sharply because of rising temperatures and unpredictable rainfall (Billman et al., 2022). This gap in forage supply calls for the use of resilient, warm-season options that can produce high biomass and keep nutritive value up during heat stress. Sunn hemp (*Crotalaria juncea* L. and *Crotalaria ochroleuca* G. Don) is a tropical leguminous plant that has become a promising answer to this seasonal shortfall (Wang et al., 2015). Known for its fast growth and excellent drought tolerance, sunn hemp can potentially accumulate high forage biomass in a short time. As a nitrogen-fixing legume, it forms a symbiosis with *Rhizobium* bacteria to turn atmospheric N into a form that plants can use, offering a sustainable fertility source for subsequent crops (Balkcom & Reeves, 2005).

While the genus *Crotalaria* is often linked to toxic pyrrolizidine alkaloids, certain cultivars have been developed for their safety and usefulness in agriculture (Mosjidis et al., 2012). This study assessed three cultivars: *C. juncea* 'Crescent Sunn', known for its quick establishment; *C. juncea* 'Loei', often chosen for its favorable leaf-to-stem ratio; and *C. ochroleuca* 'Red Mini', a different sunn hemp species with the potential to adapt to shorter growing periods (Garzon et al., 2021; Rambo, 2017). Sunn hemp plays a dual

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role in modern farming as both a cover crop and a high-quality forage. As a cover crop, it suppresses weeds and improves soil structure, while as forage, its leaves contain a high crude protein (CP) concentration that can rival traditional legumes like alfalfa (Shortnacy et al., 2023).

Management of the crop heavily depends on the timing of harvest, with 60-day intervals typically capturing the plant at its peak nutritive value during the pre-flowering stage (Garzon et al., 2021). If harvested 90 days after seeding, the plant reaches the flowering stage, providing resources for bees and other pollinators, and greater biomass accumulation and carbon sequestration (Dubeux et al., 2019). Besides monocultures, there is a strong interest in Maine for using sunn hemp in mixtures with other warm-season forages to create a more balanced and resilient pasture. However, given Maine's climate and relatively short frost-free period (140 days per year, approximately), conducting an initial evaluation for productive performance is a crucial first step. We hypothesized that at least one of the tested cultivars would show acceptable performance in biomass accumulation and nutritive value, to help overcome the summer slump and support the long-term sustainability of Maine's forage systems. The objective of this study was to evaluate the nutritive value and performance of three sunn hemp cultivars: Crescent Sunn, Loei, and Red Mini, under Maine edaphoclimatic characteristics.

MATERIALS AND METHODS

Experimental site

The study was conducted at the University of Maine J. Franklin Witter Teaching and Research Center, located in Old Town (44°55′43″ N; 68°41′45″ W, 33 m a.s.l), from June to September in 2024 and 2025. Predominant soil is Pushaw-Boothbay (Fine-silty, mixed, semiactive, nonacid, frigid Aeric Epiaquepts). Selected initial soil chemical properties include pH (in water) of 6.0, modified Morgan P, K, Mg, and Ca concentrations (0- to 15-cm depth) of 3, 102, 66, and 909 mg kg^{-1}, respectively, and 4% organic matter. Daily temperature and accumulated precipitation during the experimental period were extracted from the National Center for Environmental Information at the National Oceanic and Atmospheric Administration (NOAA) (Table 1).

Treatments consisted of three sunn hemp cultivars (Crescent Sunn, Loei, and Red Mini), arranged in a randomized complete block design with three replicates. Red Mini was only evaluated in 2025 due to a lack of seed availability in 2024.

Plots were 4 m by 4 m, with a 2-m alleyway between plots. The area was disked several times until no vegetation remained on the soil surface. Sunn hemp was seeded in a prepared seedbed with a cone seeder at a 16 kg ha^{-1} seeding rate (81% pure live seed) (Garzon et al., 2021). The soil had already reached an average temperature of 18°C, suitable for sowing warm-season forage species in Maine. The seeds were not inoculated because no specific sunn hemp inoculants were available from the market in Maine.

TABLE 1 Accumulated monthly precipitation and average temperature in Old Town (ME) during June to September in 2024, 2025, and the 10-year average.

Variable	2024	2025	10-year average
Precipitation (mm)			
June	124	80	86
July	82	40	80
August	108	33	89
September	30	84	95
Temperature (°C)			
June	18	17	16
July	21	21	20
August	19	19	19
September	15	15	15

Two 0.25 m^2 areas were harvested per plot, at 60- and 90-days postseeding, corresponding to preblooming and full blooming state, with a sickle knife at ground level, and used to calculate the average biomass accumulation per plot on a dry matter (DM) basis. Two subsamples of approximately 500 g were taken, dried at 60°C for 72 h, ground to pass a 1-mm screen in a Wiley mill (Thomas Scientific), and used for CP, neutral detergent fiber (NDF), non-fiber carbohydrates (NFC), lignin, and NDF digestibility at 30 h determinations by NIR analyses in the DairyOne® lab. The validation of predicted results was assessed through wet chemistry analysis of CP, NDF, and NFC on 20 randomly selected samples from the same batch analyzed by NIRS. Reported fit statistics included R^2 values as high as 0.82, standard error of prediction as low as 2.4, and bias as low as ±1.2 (Table S1) (Castillo et al., 2025).

Before the biomass sampling, preharvest canopy height was also evaluated with a measuring stick at five random locations per plot.

For biological N fixation analysis, two grams of plant tissue were ball-milled, using the Mixer Mill MM 400 (Retsch) at 25 Hz for 9 min. Samples were analyzed for $\delta^{15}N$, using an isotope ratio mass spectrometer (Isoprime 100, Isoprime) interfaced in continuous flow with an elemental analyzer (MICRO cube, Elementar). N isotope ratio is reported in parts per thousand (‰) using standard delta (δ) natural abundance. The contribution of N derived from the atmosphere (Ndfa) to sunn hemp was calculated from comparing the ^{15}N abundance in sunn hemp and unfertilized timothy grass, collected from areas adjacent to the experiment, as non-N_2-fixing reference plants (Garzon et al., 2023). The B value for *C. juncea* was −1.4‰, as reported by Okito et al. (2004). Atmospheric N fixed (kg N fixed ha^{-1}) was calculated by multiplying the Ndfa proportion (%) by the plant

N concentration (%) and forage accumulation (kg DM ha^{-1}) per plot.

Statistical analysis

Statistical assumptions were verified in all the responses. Data were analyzed by fitting linear mixed models. Sunn hemp cultivar, harvest, and year treatments were analyzed as fixed effects. Blocks and their interactions were considered random effects. Response variables were biomass accumulation, CP, NDF, NFC, lignin, NDF digestibility, Ndfa, and N content. They were analyzed by fitting nonlinear models and analysis of variance (ANOVA). Data were analyzed with RStudio software, using the nonlinear least squares function from the stats package for the calculation of nonlinear models, the fit linear mixed-effects model function of the lme4 package for ANOVA, and the emmeans package for post hoc analyses to mixed models (RStudio Team, 2025). Treatments were considered different when $p \leq 0.05$. Treatments and interactions not discussed were not significant ($p > 0.05$).

RESULTS

Weather responses

There were fewer rainfall events in the summer of 2025, with 31% less precipitation than in 2024 (343 vs. 236 mm accumulated from June to September 2024 and 2025, respectively) (Table 1), and some areas were declared as experiencing "Extreme Drought" by the US National Weather Service in 2025.

The air temperature was similar during the summer months of both years, with an average of 18.3°C versus 18.0°C in 2024 and 2025, respectively, with an average range of 12°C to 25°C in both years.

Biomass accumulation and height

There was a year × harvest interaction in biomass accumulation (Table 2). This interaction occurred due to a greater accumulation in 2024 (4296 vs. 1099 kg DM ha^{-1} for 2024 and 2025, respectively, SE = 95, $p < 0.01$). Additionally, all cultivars accumulated more biomass at 90 days. Sunn hemp height also followed a similar pattern, with differences between years (134 vs. 41 cm for 2024 and 2025, respectively, SE = 2, $p < 0.01$), and greater size at 90 days (Table 2).

Furthermore, when examining the cultivars separately by harvest dates and year, similar biomass accumulation was observed for Crescent Sunn and Loei, while Red Mini showed a lesser response (Figure 1). In 2025, Red Mini maintained a lower height than the other cultivars, measuring 13 and 64 cm at 60 and 90 days, respectively (SE = 2, $p = 0.03$).

TABLE 2 Year × harvest interaction for sunn hemp biomass accumulation and height.

Year	Harvest date (days)	Biomass accumulation (kg DM ha^{-1})	Height (cm)
2024	60	3002aA	119bA
	90	5590bA	158aA
	SE	189	1.3
	p	0.003	<0.0001
2025	60	8038aB	48bB
	90	1396aB	64aB
	SE	72	3.5
	p	0.228	0.007

Note: Means followed by the same lowercase letters are not different when comparing harvest dates within years ($p \geq 0.05$). Means followed by the same uppercase letter are not different when comparing a harvest date between years ($p \geq 0.05$).
Abbreviation: SE, standard error.

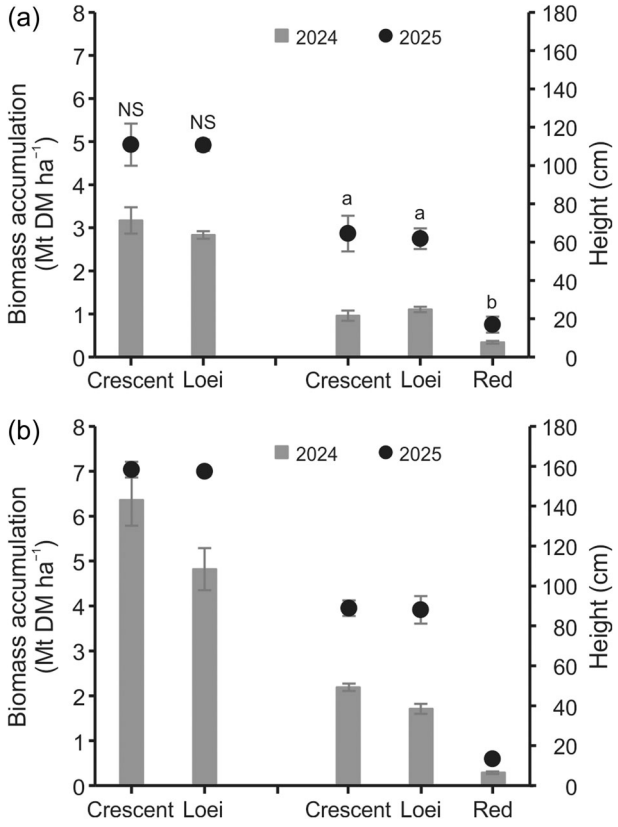


FIGURE 1 Biomass accumulation and height of sunn hemp cultivars by year in (a) 60-day harvest and (b) 90-day harvest. Means followed by the same lowercase letter within cultivar are not different ($p \geq 0.05$) for biomass accumulation on a dry matter basis (DM) and height. NS, not significant.

Nitrogen fixation

There were a year and harvest effects on the proportion of Ndfa and N content. Sunn hemp showed 54% higher Ndfa in 2025 compared to 2024, and 25% higher at 90 days compared to 60 days after harvest. A similar trend was observed with N content at harvest, with a

difference of 24 kg N ha^{-1} between 60 and 90 days. Additionally, there was a higher N content in 2024, possibly related to the greater biomass accumulation that year (Table 3).

Furthermore, Crescent Sunn and Loei showed greater Ndfa than Red Mini at 60 days harvest in 2025 (45.6%, 49.4%, and 36.4% Ndfa, respectively, SE = 6, $p > 0.05$), with no statistical differences at 90 days (53.4%, 70.0%, and 56.9% Ndfa, respectively, SE = 6, $p < 0.05$).

Nutritive value

There was a year × harvest interaction between all variables evaluated for nutritive value (Table 4). Lignin and NDF proportions were greater at 90 days in both years, although there were no statistically significant differences in NDF in 2025, possibly due to high variability among samples. There was a decrease in NFC and digestibility at 90 days in both years, and in CP between the two harvests in 2025. Lastly, sunn hemp nutritive value was greater in 2025, due to higher values for CP, NFC, and digestibility, and lower values for NDF and lignin, compared to 2024 (Table 4).

TABLE 3 Year and harvest effects on sunn hemp proportion of nitrogen derived from the atmosphere (Ndfa) and nitrogen content.

Variable	Ndfa (%)	Nitrogen content (kg N ha^{-1})
Year		
2024	33.8	74.3
2025	52.0	25.0
SE	0.9	1.7
p	0.0002	0.0006
Harvest date (days)		
60	38.2	37.9
90	47.6	61.9
SE	2.0	3.0
p	0.06	0.02

Abbreviation: SE, standard error.

TABLE 4 Year × harvest interaction on sunn hemp crude protein (CP, %), neutral detergent fiber (NDF, %), lignin (%), non-fiber carbohydrates (NFC, %), and NDF digestibility at 30 h (Digest, %).

Year	Harvest date (days)	CP	NDF	Lignin	NFC	Digest
2024	60	11.9aB	44.3bA	6.0bA	32.0aA	47.6aB
	90	10.0aB	48.1aA	12.1aA	25.2bB	26.6bB
	SE	0.2	0.6	0.2	0.6	0.8
	p	0.32	0.001	<0.0001	0.02	0.0003
2025	60	22.4aA	39.8aA	4.8bA	25.6bB	60.3aA
	90	14.0bA	43.6aB	9.5aB	34.6aA	44.8bA
	SE	0.3	0.6	0.1	0.5	0.6
	p	0.0002	0.9	0.0007	0.0005	0.009

Note: Means followed by the same lowercase letters are not different when comparing harvest dates within years ($p \geq 0.05$). Means followed by the same uppercase letter are not different when comparing a harvest date between years ($p \geq 0.05$).

Abbreviation: SE, standard error.

DISCUSSION

Biomass accumulation

Sunn hemp is a fast-growing legume with significant biomass production potential, accumulating up to 5600 kg DM ha^{-1} in 60 days (Garzon et al., 2021). However, its performance typically declines at higher latitudes. While the extended photoperiod in northern regions maintains the plant in a prolonged vegetative state by delaying floral induction, the total number of long, warm days available is insufficient to maximize growth. Consequently, the shorter duration of the favorable growing season in the north limits total biomass accumulation compared to southern latitudes, where a higher frequency of productive days allows for superior performance. Naumann et al. (2025) reported that sunn hemp accumulated 1864 kg DM ha^{-1} after 60 days of planting in Missouri, while Stute and Shekinah (2019) recorded an average production of 3900 kg DM ha^{-1} in Wisconsin. The values reported in our experiment fall within the range of these studies (Table 2). Sunn hemp is sensitive to photoperiod; fewer hours of sunlight decrease its photosynthesis rate, carbon sequestration, and biomass buildup (Balkcom et al., 2011). Stute and Shekinah (2019) noted in Wisconsin that "sunn hemp is a highly photosensitive crop, and its growth and biomass accumulation are greatly affected by growing degree days. It is responsive to planting date when grown as a warm-season cover crop."

Moreover, sunn hemp is a plant with moderate drought tolerance, capable of surviving and performing reasonably well under medium water stress conditions. Alapati et al. (2025) found that sunn hemp can withstand irrigation levels as low as 50% of field capacity replenishment while maintaining good performance. They concluded that sunn hemp can tolerate medium drought stress, with the plant maintaining superior aboveground biomass, height, and chlorophyll content. Shortnacy et al. (2023) showed that water limitation significantly reduces sunn hemp biomass, with dryland conditions producing about 84% less biomass than irrigated conditions. In our experiment, we observed a 3.7 and four-fold reduction in biomass at 60 and 90 days, respectively, between 2024 and 2025 (Table 2). This likely relates to the marked decrease in precipitation between the 2 years (344 vs. 236 mm of total rainfall from June to September in 2024 and 2025). Maine experienced areas impacted by severe and extreme drought in some regions in 2025 (NOAA, 2025). During the first 2 months of establishment (June and July), sunn hemp received 205.7 and 119.7 mm of rain in 2024 and 2025, respectively (Table 1). This difference clearly limited plant growth and development in 2025, with

lower biomass and height values at 60 and 90 days (Table 2).

Meanwhile, Red Mini showed less height and biomass accumulation compared to Crescent Sunn and Loei (Figure 1). Garzon et al. (2021) reported that Red Mini accumulated three times less biomass than Crescent Sunn at 60 days postplanting in South Florida (1010 vs. 3360 kg DM ha^{-1}) but still exhibited greater growth than Red Mini in Maine. Grabowski and Williams (2020) documented a biomass accumulation of 1455 kg DM ha^{-1} for Red Mini in Florida in 2016, with plants reaching an average height of 36 cm. Red Mini is a specific cultivar bred mainly for use as a high-quality cover crop and green manure (Silva et al., 2024). While standard sunn hemp is known for being a large, fibrous plant, Red mini is distinguished by a shorter growth habit and rapid decomposition (Garzon et al., 2021).

Nitrogen fixation

Sunn hemp contributed approximately 50 kg N ha^{-1} through biological N fixation, with up to 52% Ndfa (Table 3). Parvin et al. (2022) found that sunn hemp fixed 46–55 kg N ha^{-1} in field trials, with 39%–73% Ndfa. Perin et al. (2004) confirmed biological N fixation rates of 57%–61%, incorporating 89–173 kg N ha^{-1} into the soil. Jaramillo et al. (2020) reported 33%–56% Ndfa with Crescent sunn in North Florida. All these results show that sunn hemp is a highly effective nitrogen-fixing legume.

Additionally, it was also observed that environmental and crop management factors influence N fixation. Drought significantly impairs N fixation in sunn hemp through complex physiological mechanisms that reduce nodule activity and N accumulation. Key mechanisms include reduced phloem flow into nodules, carbon shortage in nodule metabolism, and potential N feedback inhibition (Serraj et al., 1999).

Castellano-Hinojosa et al. (2022) demonstrated that stress and drought may affect sunn hemp N fixation by 30% to 40%, with nodules experiencing significant metabolic disruptions. However, a greater proportion of Ndfa was observed in 2025 in our study (Table 3). This may have resulted from the lower soil moisture, which decreases the nitrification process in the soil. With less available N in the soil, sunn hemp may have had to rely more on biologically fixed N, even with possible metabolic disruptions in its root nodules.

Furthermore, the fixed N content depends on the Ndfa proportion and the sunn hemp biomass accumulation. Therefore, even though N fixation was higher in 2025, sunn hemp contained a lower N content because biomass accumulation was heavily impacted by that year's climatic conditions (Table 1). This connection with biomass also explains why the fixed N content was higher at 90 days after harvest compared to 60 days (Table 3).

Despite poor performance due to drought in 2025, sunn hemp managed to provide 25 kg ha^{-1} of biologically fixed N, which covers at least half of the recommended annual N application for pasture maintenance (McKenzie et al., 2003; Viljoen et al., 2020).

Nutritive value

Sunn hemp is a fast-growing legume. To support its growth, the plant needs to increase the proportion and content of low-solubility supporting tissues and raise lignin levels (Salisbury & Ross, 1978). This was observed in all sunn hemp cultivars over the 2 years of evaluation. Lignin and NDF concentrations rose from 60 to 90 days after harvest, while NFC and digestibility declined (Table 4). Additionally, CP concentration was higher in 2025, showing a similar trend to Ndfa proportions in both years. Similarly, a slower growth rate could have resulted in reduced deposition of low-solubility fiber, which may have comparatively increased the CP proportion in 2025.

On the other hand, CP concentration remained steady with Crescent Sunn and Loei in 2024, despite increases in biomass and low-solubility fiber (Table 4). Lepcha et al. (2019) showed that, while overall CP declined with maturity, leaf CP stayed stable at 28.1% DM even at 55 days, whereas stem CP dropped significantly to only 8.1% DM. This different response indicates that CP concentration in whole-plant samples may depend on the leaf-to-stem ratio at harvest. Since stems make up most of the total forage mass at harvest after 45 days, the dilution effect of increasing stem biomass with lower protein content conceals the stability of leaf protein levels. This suggests that sunn hemp might produce more leaves when not water-stressed, which could result in a similar CP value between the two harvests (Table 4).

According to Lepcha et al. (2019), fresh sunn hemp harvested at 35–45 days after planting reached 79% digestibility, but it dropped to 62% at 55 days. Other research has indicated sunn hemp digestibility ranging from 48% to 68% at 50–60 days post-planting (Garzon et al., 2021; Jaramillo et al., 2020; Lepcha et al., 2019; Silva et al., 2023).

Furthermore, sunn hemp showed improved nutritive value in 2025 compared to 2024, reflected in a lower proportion of NDF and lignin and a higher concentration of CP, NFC, and digestibility (Table 4). Eberle and Shortnacy (2021) demonstrated a consistent pattern where drought-stressed sunn hemp exhibited superior nutritive value compared to irrigated crops. This manifested as higher CP, TDN, and relative feed value, and lower fiber concentrations (both ADF and NDF) under water-limited conditions. The nutritive value achieved under both conditions was comparable to premium-quality alfalfa hay.

Possible factors influencing increased nutritive value caused by drought include: (a) Growth rate modulation: under irrigation, sunn hemp exhibits faster growth rates, leading to higher fiber concentration and consequently lower nutritive value. Drought conditions slow growth, reducing fiber accumulation; (b) Cell wall composition: drought conditions may decrease fiber concentration, which could enhance nutritive value by reducing the structural carbohydrate fraction; (c) Drought resistance traits: sunn hemp has inherent drought resistance that allows it to maintain growth and nutritive value under water-limited conditions. This suggests physiological mechanisms that prioritize nutrient accumulation over

vegetative growth during stress; and (d) Biomass allocation efficiency: the similar biomass accumulation observed in rainfed and irrigated conditions indicates efficient biomass allocation patterns that sustain productivity (Shortnacy et al., 2023).

It is important to consider these nutritional differences based on the intended use of sunn hemp. Cutting at 60 days results in higher nutritive value but less biomass accumulation. At 90 days, there is more plant material, but with a higher proportion of low-solubility fibers and nutrients bound to lignin (Table 4). Harvesting sunn hemp at 60 days is more advisable from an animal nutrition perspective if it will be used as forage (Wanapat et al., 2021), while as a cover crop, it should be cut and incorporated into the soil at 60 days for rapid nutrient release and utilization by the next crop, or at 90 days for slower nutrient release and longer-term nutrient utilization (Garzon et al., 2021).

CONCLUSIONS

The study shows that Crescent Sunn and Loei Sunn hemp cultivars are highly suitable for forage production, providing a viable option for high-latitude livestock systems. Choosing sunn hemp cultivars in Maine, therefore, requires a careful decision between maximizing biomass and ease of mechanical handling. Sunn hemp reached up to 52% Ndfa, suggesting that native rhizobia in Maine soil can effectively colonize. However, as N content peaked at 74.3 kg N ha^{-1} in 2024, further research should explore whether specialized tropical rhizobial strains could improve fixation rates under Maine's cold soil temperatures.

The resilience of this species was especially clear during the extreme drought of 2025. While the water shortage predictably reduced overall biomass growth, it surprisingly enhanced the nutritive value of the forage. Additionally, despite the drought's severity, sunn hemp kept producing biomass and relied more on biological N fixation, contributing up to 25 kg N ha^{-1}. This contribution is important as it partly meets the nitrogen needs of a standing pasture or a subsequent cash crop. This change in plant strategy, depending more on atmospheric N (52% Ndfa in 2025 vs. 33.8% in 2024) when soil nitrification is suppressed by low moisture, highlights the crop's dependability in unpredictable climates.

The usefulness of sunn hemp as a cover crop is clarified by when it is terminated, which affects the rate of nutrient cycling. Terminating the crop at 60 days allows for a quick release of nutrients, benefiting the next crop immediately. Moreover, delaying termination to 90 days results in more fibrous biomass, leading to a slower release of nutrients that helps sustain soil fertility for the following year's crops. This longer growth period not only improves long-term nutrient availability after soil incorporation but also increases carbon sequestration by accumulating more biomass through photosynthesis. Overall, these results show that sunn hemp is a versatile, effective tool that can boost both immediate crop productivity and the long-term health of Maine's agricultural land.

AUTHOR CONTRIBUTIONS

Jaime Garzon: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; visualization; writing—original draft. **Edgar Cardenas**: Conceptualization; validation; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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