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High retention of N P nutrients, soil organic carbon, and fine particles by cover crops under tropical climate

Qingren Wang · Yuncong Li · Waldemar Klassen · Ashok Alva

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Abstract Soil and water conservation is a major challenge for the development of sustainable agriculture. Leaching and runoff of soil nutrients and fine particles negatively impact soil fertility, soil quality, and contribute to surface water eutrophication and sediment accumulation. Such issues are especially critical in a tropical or subtropical region, such as in south Florida with high rainfall and shallow aquifer. So far, little is known about soil particle and nutrient retention by cover cropping under contrasting rainfall intensity. Here, a pot experiment was conducted with four cover crops and two simulated rainfall rates, a low rate of 5.8 mm day⁻¹ and a high rate of 11.6 mm day⁻¹, to study the transport of N, P, and fine soil particles down the soil profile. The cover crops were sunn hemp, velvetbean, cowpea, and sorghum sudangrass in contrast to weedy fallow as a control. Results show that under low rainfall rate, total N in leachates of 0.5–1.9 kg ha⁻¹ for cover crops was much lower than 10.2 kg ha⁻¹ for fallow. Under high rainfall rate, total N in leachates ranged from 3.4 to 16.1 kg ha⁻¹ for cover crops and 8.8 kg ha⁻¹ for fallow. Cover cropping with sunn hemp was the most effective at retaining soil nutrients because of its large plant biomass production. Indeed sunn hemp biomass accumulated 376 and 247 kg N ha⁻¹ and 27 and 22 kg P ha⁻¹ under high and low rainfall rates. We also found that soil organic carbon

associated with fine soil particles in the root zone under sunn hemp and sorghum sudangrass was 5–7% greater than soil organic carbon in fallow. This study demonstrates that growing sunn hemp and sorghum sudangrass cover crops can conserve soil fine particles and nutrients against leaching and reduce adverse impacts on surface water.

Keywords Cover crop · Nutrient leaching · Soil conservation · Soil particle · Legume

1 Introduction

Contamination of surface water and groundwater with nitrate (NO₃⁻) and phosphorus (P) through runoff and leaching from agricultural land may threaten both natural terrestrial and marine ecosystems and pose a potential health hazard to humans and animals (Dorsch et al. 1984; Nielsen and Lee 1987). Nitrate losses via soil runoff and profile leaching tend to be exacerbated in fallow soils (Campbell et al. 1984, 1994) and by poor soil and crop management practices such as keeping the land fallow or without enough plants to cover the entire land (Linville and Smith 1971; Hallberg 1989). Cover crops grown during the rainy summer in humid tropical or subtropical regions can reduce soil N leaching and runoff by as much as 88% and sequester soil N up to 250 kg ha⁻¹ in plant biomass (Wang et al. 2005). For example, a number of researchers have demonstrated that cover crops or catch crops can minimize the residual soil NO₃-N level and reduce its concentration in leachate via scavenging soil nutrients resided from previous crop in either field or pot studies (Karlen and Doran 1991; Miller et al. 1992, 1994; Brandi-Dohrn et al. 1997; Wang et al. 2005). The nutrients accumulated in summer cover crop biomass when incorporated into the soil can be released to the winter crops (Wang et al. 2005, 2007).

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Soil nutrient leaching is an important concern in humid tropical and subtropical regions prone to high rainfall events. In the subtropical region of Florida, up to 76% of the total average annual rainfall (1,400 mm) occurs during the summer (Wang et al. 2005). In this region, vegetable production primarily occurs during the winter season because of the favorable weather, while the summer is considered an off season. Also, winter vegetable production brings much greater economic returns in this subtropical region as compared to other regions of the USA because heating is not needed under such a suitable weather. Summer production in this region requires increased costs to control pests and diseases and is less competitive for market compared to northern part of the USA where vegetables are mostly produced through summer (Wang et al. 2003a). Therefore, the loss of residual nutrients through leaching, due to intensive rainfall, from bare or weedy fallow soil during the hot and rainy summer is an environmental concern. In addition, the dominant soil type (81%) in this region is Krome gravelly loam soil (USDA 1996), which consists of up to 60% gravel, and has low water- and nutrient-holding capacities (Wang et al. 2003b).

In the temperate climate zone, winter cover crops, such as ryegrass and hairy vetch, sown in fall surviving through winter and regrowing in spring, play an important role in reducing nutrient leaching. For example, cover crops grown after the harvest of a cash crop capture residual soil nitrate in the fall through spring and thereby reduce nitrate leaching (Power and Doran 1988; Martinez and Guiraud 1990; Brandi-Dohm et al. 1997; Hansen and Djurhuus 1997). In contrast, cover crops may increase the risk of NO_3^- leaching in the long run due to increased organic matter input, which can contribute to increased NO_3^- following decomposition of crop residues and mineralization (Hansen et al. 2000). In sorghum and cotton production systems with sandy loam soils of southern Georgia, NO_3^- leaching decreased by 29–94% for nonlegume cover crops, such as rye (*Secale cereale* L. spp. *cereale*), compared to –6% to 48% for legume cover crops, e.g., hairy vetch (Meisinger et al. 1991; McCracken et al. 1994). Similarly, Kuo et al. (1995) found that rye and annual ryegrass (*Lolium multiflorum* Lam.) significantly reduced the NO_3^- concentration in the soil leachate compared with no cover crop treatment, whereas hairy vetch substantially increased the NO_3^- concentration in the leachate. They concluded that because of the extensive root systems of rye and annual ryegrass and their early establishment in the fall, these winter cover crops were able to scavenge residual NO_3^- from the soil and reduce NO_3^- leaching more effectively than hairy vetch.

Generally, the quantities of N and ortho-P leached depend on: (1) amount of soil nutrients present, (2) mobility of nutrients (e.g., N as compared to P), (3) solubility of nutrients (e.g., P in calcareous vs. acidic soil), (4) quantity and intensity

of rainfall, and (5) growth status and biomass of crops covering the land (White 1973; Schreiber and McDowell 1985). In south Florida, as much as 91% of irrigated water was retained by sunn hemp but only 48% by weedy fallow. Losses of soil N and ortho-P through leaching were reduced by up to 88–94% and 50–83%, respectively, by sunn hemp as compared to those from fallow (Wang et al. 2005).

In flat terrain with soil containing up to 60% gravel in tropical and subtropical regions (e.g., south Florida), transport of soil fine particles including both mineral and organic fractions down the soil profile plays a major role in influencing fertility of the top soil. The Krome gravelly soil was formed from the sedimentary oolitic limestone bedrock by mechanical scarification and subsequent pedogenic processes, which are accelerated by weathering. Thus the soil profile is very shallow (<20 cm) and it consists of 60% rock fragments (0.5–5 cm) and only 40% soil, which is prone to nutrient leaching to the shallow aquifer (about 100 cm). Because this soil contains so much gravel and rainfall is intensive during summer, fine soil particles are subject to leach down the soil profile. To overcome the drawbacks of soil compaction by rainfall and increase the soil depth, local growers have to disk the land and raise beds (30 cm high) to grow crops. Soil particles with size of >0.05 mm are intermediate between plant debris and soil mineral-associated particles, and constitutes an uncomplexed fraction of soil organic matter, partially decomposed plant and animal residues, fungal hyphae, spores, root fragments, and seeds (Cambardella and Elliott 1992; Causarano et al. 2008). The downward migration of such fine soil particles is especially important in Krome gravelly loam soil. Therefore, it is critically important to conserve soil and water in the region by growing certain cover crops rather than leaving the land fallow during the rainy summer.

The objectives of this study were to (1) quantify biomass production associated with nutrient accumulation of various cover crops; (2) evaluate leaching loss of soil nutrients, i.e., $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and ortho-P; and (3) elucidate the downward migration of fine soil particles with different cover crops in a gravelly loam soil under two different rates of simulated rainfall.

2 Materials and methods

2.1 Soil characteristics

Krome gravelly loam soil (loamy skeletal, carbonatic, hyperthermic Lithic Udorthents) used for the experiment was collected (0–10 cm) from the field of Tropical Research and Education Center, University of Florida, Homestead, FL, USA. The soil contained 29.2×10^3 mg kg^{-1} organic C, 982.3 mg kg^{-1} total N, 46.8 mg kg^{-1} AB-DTPA extractable P, and 682×10^3 mg kg^{-1} CaCO_3 equivalent with pH (KCl) 7.8–

8.2. The soil consisted of 58.8% gravel (>2 mm). The particle size distribution was 40.8% sand, 39.7% silt, and 19.5% clay in the gravel-free fraction (Miller and Miller 1987).

2.2 Experimental design and management

Plastic pots of 23 cm diameter on the top and 20 cm diameter at the bottom, and 32 cm deep with 8 kg air-dried soil were used. The experiment was conducted following a split plot design with two rates of simulated rainfall (main factor) and four cover crop species (subfactor) with four replicates. The soil depth in pots was comparable to the field conditions with 30 cm raised beds.

Rainfall rates were 5.8 and 11.6 mm day⁻¹, which are comparable to the average rainfall of the growth period (8.7 mm ± 33%), i.e., 76% of 1,380 mm total occurs in 4 months (June to October). Before seeding, a fertilizer blend [10–4.3–8.3 of N–P–K (%)] at 2.3 g pot⁻¹ equivalent to 55, 24, and 46 kg ha⁻¹ of N, P, and K, respectively, was mixed into the soil. The 10% N in the fertilizer consisted of NO₃-N, NH₄-N, water-soluble N or urea N, and water insoluble N at 2.0%, 6.0%, 1.8%, and 0.2%, respectively. Three legume summer cover crops, i.e., sunn hemp (*Crotalaria juncea* L.), cowpea (*Vigna unguiculata* L.), and velvetbean (*Mucuna pruriens* var. *utilis*), and one nonlegume cover crop, sorghum sudangrass (*Sorghum bicolor* × *S. bicolor* var. *sudanense*), were used. A treatment with no cover crop as weedy fallow was included as a control (i.e., without pulling out weeds). Plant densities maintained in the pot for different cover crops were equivalent to seeding rates in the field, i.e., ten plants for sunn hemp and sorghum sudangrass, and five plants for velvetbean and Cowpea. The field seeding rates (Wang et al. 2009) were: 75, 60, 50, and 140 kg ha⁻¹ for sunn hemp, sorghum sudangrass, velvetbean, and cowpea, respectively. The corresponding seed sizes were 38.1, 28.6, 753.6, and 243.6 g/1,000 seeds. There were two to three weeds in each pot for fallow without sown and the dominating species were pigweed (*Amaranthus retroflexus* L.), black nightshade (*Solanum physalifolium* Busby), and yellow nutsedge (*Cyperus esculentus* L.).

To simulate different rainfall rates, a microsprinkler (Dan 2001PC, Point South Irrigation) was installed in the center of each pot to ensure the water spread evenly within the pot and adjusted to deliver 2 or 4 Lh⁻¹ (equivalent to 5.8 or 11.6 mm day⁻¹) with a hose faucet (model 62,401, Irrigation Products Inc., North Salt Lake, UT, USA). Water uniformity of sprinkler delivery was monitored by measuring water quantities received in the same size containers with three extra sprinklers for each rate placed at different positions in the zone of water delivery. During the first 2 weeks, the soil surface moisture was maintained by hand spraying for seed germination and seedling establishment without causing leaching. As of the third week when cover

crop seedlings were uniformly established, each pot was placed above a plastic pan (21 cm diameter and 10 cm deep) supported by a polyvinyl chloride ring (15 cm diameter and 5 cm high) to avoid soil percolation. The leachate was collected every day and the volume was recorded, pooled across a week, stored at 4°C for chemical analyses.

2.3 Sampling and analyses

Prior to planting, 2 cm diameter core soil sample was collected from the center of five randomly selected pots to determine the soil bulk density, i.e., 1.43 g cm⁻³ ± 12%. All sampling holes were refilled with the same soil. The soil samples were ground to pass through a 2-mm sieve for chemical analyses. Ten weeks after planting, cover crops were cut at the soil surface. The roots were washed free of soil and the plant parts were cut into 1–2 cm long pieces, dried at 70°C for 72 h, and dry weights were recorded. The leachate samples were filtered through a 0.45 µm membrane and concentrations of NO₃-N, NH₄-N, and ortho-P were analyzed colorimetrically (US EPA 1993) using an Auto-analyzer, AA-3 (BRAN-LUEBBE, Germany). The detection limits for the above analytes were 0.02, 0.01, and 0.002 mg l⁻¹, respectively. Concentrations of N and C in soil and plant samples were analyzed using a CNS Auto-analyzer (vario Max Elementar, Hanau, Germany).

An intact core (5 cm diameter) soil sample was collected from the center of each pot across the entire profile after harvesting the cover crops using a polycarbonate tube with a sharp end. Each soil core was sliced into 10 cm increments. Root biomass weight and volume in the cores were determined and excluded for bulk density calculation, and these roots were washed free of soil and accounted for total root biomass. The soil samples were air dried, ground to pass a 2-mm sieve, and particle size analysis was conducted using the micropipette method (Miller and Miller 1987). The soil was wet-sieved using a set of sieves with 1.0, 0.25, and 0.053 mm diameter openings (Causarano et al. 2008) to separate sand, silt, and clay fractions. The concentrations of soil organic carbon (0.58 × soil organic matter) in these fractions were determined via modified weight loss on ignition method (Wang et al. 2010). Equivalent amounts of soil particles redistributed after the experiment were estimated based on the pot surface area and soil bulk densities determined at corresponding soil layers. The quantity of organic matter in each fraction (clay, silt, and sand) was calculated by integrating the total weight of respective fraction in the corresponding depth of the soil with its organic matter concentration determined as above.

2.4 Statistical analysis

The data were subjected to the analysis of variance (ANOVA) for a split plot design with a mixed model using SAS program

(SAS Institute, version 9.1.3, 2004). Duncan's multiple range test was used to separate means for a significant difference level of $\alpha=0.05$ for the amounts of leachate, nutrients, cover crop biomass, and particle size redistribution.

3 Results and discussion

3.1 Amounts of biomass and nutrients accumulated by various cover crops

The cover crop biomass as well as total N and P in the biomass were significantly influenced by rainfall rate, cover

crops, and the interaction effects between the two factors (Table 1). The cover crop biomass, and total N and P in the biomass were greater with high rainfall rate as compared to those with low rainfall rate. Among cover crops, sunn hemp accumulated the greatest quantity of biomass and N, followed by velvetbean. Sunn hemp and velvetbean accumulated greater amount of P than that by the other cover crops regardless of rainfall rate. However, under the high rainfall rate, sunn hemp biomass production and total N were greater while leaching of N and P were lower than those of the remaining treatments. The highest amounts of N and P occurred in cowpea and fallow treatments, respectively. Under the low rainfall rate, the biomass

Table 1 Analysis of variance (ANOVA) and mean separation statistics for biomass production of cover crops and mass balance of N and P across two rainfall intensities

Rainfall rate and cover crop	Biomass (shoots+roots)	Plant uptake		Fertilizer input		Leaching loss		Net gain (+) or loss (-)	
		N kg ha ⁻¹	P	N	P	N	P	N	P
High rainfall (11.6 mm day ⁻¹)									
Sunn hemp	15,123 a	379 a	28 a	55	24	3.4 c	1.2 c	320 a	3 a
Velvetbean	9,842 b	268 b	26 a	55	24	6.0 c	1.7 c	207 b	1 ^a
Cowpea	3,980 c	104 c	12 a,b	55	24	16.1 a	3.2 b	33 c	-15 a,b
Sorghum sudangrass	4,035 c	28 d	8 b	55	24	4.0 c	3.0 b	-31 d	-19 b
Fallow	642 d	8 d	2 b	55	24	8.8 b	4.5 a	-56 d	-27 b
Low rainfall (5.8 mm day ⁻¹)									
Sunn hemp	9,898 a	247 a	19 a	55	24	0.5 c	0.3 c	191 a	-6 a
Velvetbean	8,164 a	221 a	22 a	55	24	0.6 c	0.3 c	166 a	-2 a
Cowpea	3,345 b	86 b	10 b	55	24	1.9 b	0.8 b	29 b	-15 b
Sorghum sudangrass	3,706 b	26 c	7 b,c	55	24	1.2 b	0.8 b	-31 c	-18 b,c
Fallow	651 c	9 d	2 c	55	24	10.3 a	2.0 a	-56 c	-24 c
Mean (rainfall)									
High	6,724 a	157 a	15 a			7.7 a	2.7 a	94 a	-12 a
Low	5,153 b	118 b	12 b			2.9 b	0.8 b	60 b	-13 a
Mean (cover crop)									
Sunn hemp	12,511 a	313 a	23 a			2.0 b	0.8 c	256 a	-1 a
Velvetbean	9,003 b	245 b	24 a			3.3 b	1.0 c	186 a	-1 a
Cowpea	3,663 c	95 c	11 b			9.0 a	2.0 b	31 b	-15 b
Sorghum sudangrass	3,871 c	27 d	8 c			2.6 b	1.9 b	-31 c	-18 b,c
Fallow	647 d	8 e	2 d			9.6 a	3.3 a	-56 c	-26 c
ANOVA ($P \geq F$)									
Rainfall (R)	9.97***	8.88**	6.32*			4.28**	3.12*	45.62**	2.12 ^{NS}
Cover crop (C)	75.52***	83.50***	43.88***			6.12**	2.18*	35.38**	4.26*
R × C	3.86*	3.48*	1.87 ^{NS}			2.65*	1.82 ^{NS}	4.12*	2.13 ^{NS}

Values followed by same letters within the same column by each treatment comparison represent no significant difference (0.05)

* $p=0.05$, significance

** $p=0.01$, significance

*** $p=0.001$, significance

NS not significant

production, and quantities of N and P accumulated were significantly greater while leaching of N and P were lower in sunn hemp and velvetbean than those for the other treatments. The plant biomass accumulation and quantity of P in the biomass were similar between cowpea and sorghum sudangrass at both rainfall rates.

The nutrient mass balance (Table 1) by subtracting fertilizer input and leaching loss from plant uptake showed that all the three legume cover crops, sunn hemp, velvetbean, and cowpea had net gains of N at both high and low rainfall rates, while the rest of treatments had net losses of N. This result indicates that all these legumes, especially sunn hemp and velvetbean, can accumulate more N from the soil and/or air. The N fixation from air by these legumes might be an important contribution because seven to ten root nodules for each plant of the three legumes were observed after harvest. The N fixation can be evident by comparing sorghum sudangrass with cowpea for the similar amounts of plant biomass produced but N accumulation was greater in the later than that in the former.

The quantity of N, however, was significantly greater in the cowpea biomass as compared to that in the sorghum

sudangrass because of root nodules on cowpea roots, which may also explain the greater quantity of N leached with cowpea than that with sorghum sudangrass. The biomass N was greater in sunn hemp and velvetbean as compared to cowpea. However, it corresponds to 2.4–3.8-fold greater biomass in sunn hemp and velvetbean treatments as compared to cowpea.

These results are in agreement with previous reports (Holderbaum et al. 1990; Clark et al. 1995) suggesting that some legume cover crops can serve both as a sink and a source of soil N. Both velvetbean and sunn hemp appear to be good scavengers of soil nutrients (Table 1), as is evident from decreased leaching. Cowpea seemed acting as a source to the soil N pool due to its rhizobia bacteria but low biomass production, which caused a greater amount of N leached as compared to sunn hemp and velvetbean, particularly under the high rainfall rate. In contrast, sorghum sudangrass can scavenge soil N, reduce its leaching, and grow well under the subtropical weather but the N content in the plant tissue was only 0.7% (in contrast to 2.6% in cowpea), which lead to a net N loss. To reduce N leaching, intercropping cowpea with a non-legume crop

Table 2 Total leachate volume and mean concentrations of N and ortho-P (mg L^{-1}) in the leachate of five cover crop treatments and two rates of simulated rainfall with analysis of variance (ANOVA)

Rainfall rate and cover crop	Total leachate (L)	$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N mg L}^{-1}$	Ortho-P
High rainfall (11.6 mm day ⁻¹)				
Sunn hemp	18.8 c	1.01 b	0.26 a,b	0.39 b
Velvetbean	23.0 c	1.04 b	0.37 a	0.41 b
Cowpea	40.1 b	2.48 a	0.16 b	0.52 a
Sorghum sudangrass	52.5 a	0.39 b	0.39 a	0.39 b
Fallow	51.7 a	1.17 b	0.20 a,b	0.54 a
Low rainfall (5.8 mm day ⁻¹)				
Sunn hemp	3.1 c	1.32 b, c	0.25 b	0.39 b
Velvetbean	3.4 c	1.26 b,c	0.21 b	0.56 a
Cowpea	9.6 b	1.89 a,b	0.22 b	0.55 a
Sorghum sudangrass	27.6 a	0.21 c	0.12 c	0.29 c
Fallow	25.4 a	2.86 a	0.53 a	0.50 a
Mean (rainfall)				
High rate	37.2 a	1.22 a	0.28 a	0.45 a
Low rate	13.8 b	1.47 a	0.26 a	0.46 a
Mean (cover crop)				
Sunn hemp	10.9 c	1.16 b,c	0.26 a	0.39 b
Velvetbean	13.2 c	1.15 b,c	0.29 a	0.49 a
Cowpea	24.9 b	2.19 a	0.31 a	0.54 a
Sorghum sudangrass	40.0 a	0.30 c	0.14 a	0.34 b
Fallow	38.5 a	1.98 a,b	0.36 a	0.52 a
ANOVA ($P \geq F$)				
Rainfall (R)	195.10***	0.66 ^{NS}	0.07 ^{NS}	0.06 ^{NS}
Cover crop (C)	56.54***	6.41***	0.96 ^{NS}	23.59***
$R \times C$	2.38 ^{NS}	1.88 ^{NS}	1.48 ^{NS}	6.57***

Values followed by same letters within the same column by each treatment comparison represent no significant difference (0.05)

* $p=0.05$, significant

** $p=0.01$, significant

*** $p=0.001$, significant

NS not significant

might be an option since cowpea might be able to supplement N to the non-legume (as N scavenger). In return, the non-legume may scavenge soil N to reduce the concentration of readily leachable N in the soil solution. Such a combination of legume and nonlegume biculture with a synergetic effect can produce a greater amount of total biomass than monocultures of either legume or non-legume cover crops (Sainju et al. 2006).

Compared to N, the amount of P taken up by cover crops was less than that applied except sunn hemp and velvetbean with high rainfall rate (Table 1), which indicates that some fertilizer P applied in such a rate cannot be taken up by cover crops. Net uptake of P was only 3 kg ha⁻¹ by sunn hemp despite production of 15,123 kg ha⁻¹ biomass, which implies that a high rate of P applied to such soil may cause P leaching and lead to a risk of surface or groundwater eutrophication.

3.2 Effects of cover crops and simulated rainfall rates on amounts of leachate, nitrogen and phosphorus

The ANOVA showed significant differences in leachate volumes, and the mean concentrations of N (NO₃-N and NH₄-N) and ortho-P throughout the entire sampling period (Table 2). Rainfall rate significantly influenced leachate volume but not the concentrations of NO₃-N, NH₄-N, and ortho-P. Cover crop treatments had significant differences for all of the variables except the concentration of NH₄-N. The interaction effect between rainfall rate and cover crop treatments was significant only on the concentration of ortho-P.

Under the high rainfall rate, sunn hemp and velvetbean decreased the leachate volume by 64 and 56%, respectively, as compared to that of fallow. Cowpea decreased the leachate by 22%, and there was no significant difference between sorghum sudangrass and fallow. Under the low rainfall rate, the leachate volume with either sunn hemp or velvetbean was about 87% lower than that in fallow (Table 2). Also, leachate volume for cowpea was 62% less than fallow, and there was no significant difference between sorghum sudangrass and fallow. Therefore, both sunn hemp and velvetbean were more effective in minimizing leachate volume losses under both low and high rainfall rates compared to fallow and sorghum sudangrass.

Under the high rainfall rate, the mean leachate NO₃-N concentration was significantly greater in cowpea than any other cover crops or the fallow. The NH₄-N concentration in the leachate with cowpea was lower than that with sorghum sudangrass and velvetbean. The ortho-P concentrations in the leachate were greater with fallow or cowpea compared with the rest of cover crops. Under the low rainfall, the concentrations of NO₃-N in the leachate were significantly lower with sorghum sudangrass, velvetbean and sunn hemp cover crops as compared to that in the fallow. The NH₄-N concentration in the leachate was significantly decreased by

all the cover crops as compared to that in fallow. A significant decrease in ortho-P concentration in the leachate was evident with sorghum sudangrass and sunn hemp as compared to that in all other treatments, which shows that the amount of plant biomass (e.g., sunn hemp and velvetbean), and root type (e.g., sorghum sudangrass) may play an important role in soil nutrient retention. This may indicate that at the low rainfall rate, most cover crops can accumulate N either from the air or from the soil with their considerably large amounts of biomass. However, at the high rainfall, the highest concentration of NO₃-N in the leachate was observed with cowpea, which might be related to the crop growth rate, utilization or translocation of fixed N via cowpea rhizobia from the roots to the aboveground biomass.

The concentrations of NO₃-N, NH₄-N and ortho-P in the leachate decreased by 37, 72, and 29% at low rainfall rate and 75, 79 and 32% at high rainfall rate from the first week to the second week of leachate collection (Fig. 1). Such decrease might be related to plant growth and development. As plant biomass increased, nutrient uptake by the cover crops generally increased, which also improved the conservation of soil water and nutrients by the development of plant roots, and consequently, nutrient leaching across all treatments decreased (Wang et al. 2005).

Leguminous cover crops can also contribute a considerable quantity of soil N after being decomposed. For example, the N contributions following the growth of hairy

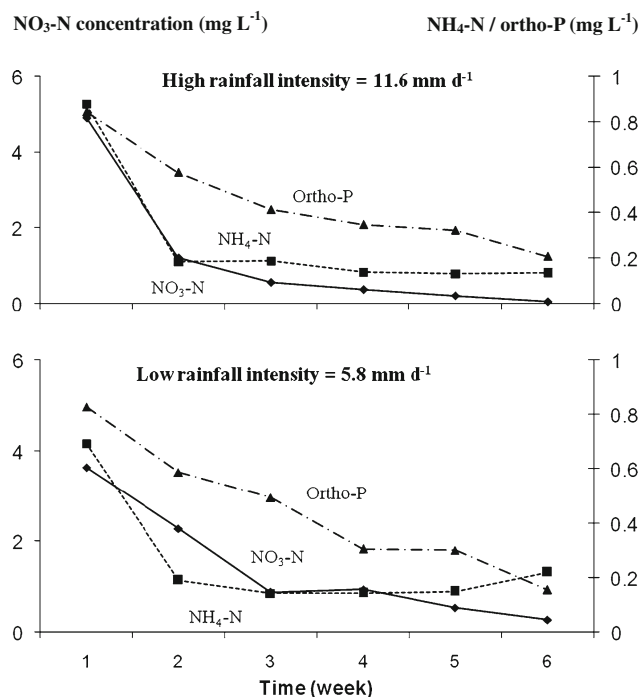


Fig. 1 Changes in concentrations of NO₃-N, NH₄-N, and ortho-P with time in the leachate from Krome gravelly loam soil with mean values across all cover crop treatments under low- and high-simulated rainfall rates

vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.), ranged from 72 to 149 kg ha⁻¹ of N (Ebelhar et al. 1984; McVay et al. 1989; Holderbaum et al. 1990; Clark et al. 1995). The total amount of N in sunn hemp biomass was 350 kg ha⁻¹ with biomass production improved through an additional cutting to induce plant branching (Wang et al. 2003a). As a result, soil fertility was improved and the yield of subsequent crop following sunn hemp was significantly improved (Wang et al. 2007, 2009). The total amounts of NO₃-N leached below 30 cm of soil depth over 3 months growing okra (*Abelmoschus esculentus*

L.) accounted equivalent to 57 and 10 kg Nha⁻¹ for the soil incorporated with sunn hemp and sorghum sudangrass residues, respectively (Wang et al. 2003b).

3.3 Effects of rainfall rate and cover crops on downward migration of fine soil particles

The redistribution of different fractions of soil fine particles (clay and silt) in the top two soil layers (0–10 and 10–20 cm) was significantly different (Table 3). Rainfall rate had a significant influence on the fraction of all three particles.

Table 3 Mass balance calculation before (B) and after (A) the experiment on soil particle downward migration for the top two layers (0–10 and 10–20 cm) influenced by five cover crop treatments and two rainfall rates, and ANOVA

Depth and cover crop	Bulk density (×1,000 kg m ⁻³)		Clay			Silt (×1,000 kg ha ⁻¹)			Sand		
	B	A	B	A	B–A	B	A	B–A	B	A	B–A
High rainfall rate=11.6 mm day ⁻¹											
0–10 cm											
Sunn hemp	1.43	1.34	279	189 a	89 b	568	626 a	-58	583	527 b	56
Velvetbean	1.43	1.34	279	177 a	101 a,b	568	594 a	-26	583	572 a	12
Cowpea	1.43	1.34	279	168 a,b	111a	568	592 a	-24	583	580 a	4
Sorghum sudangrass	1.43	1.34	279	191 a	88 b	568	611 a	-43	583	542 a,b	42
Fallow	1.43	1.35	279	151 b	128 a	568	598 a	-30	583	597 a	-13
10–20 cm											
Sunn hemp	1.43	1.42	279	231 b	48 a	568	660 a	-92	583	530 b	54
Velvetbean	1.43	1.42	279	260 a,b	19 b	568	601 a	-34	583	561 a,b	22
Cowpea	1.43	1.42	279	275 a	4 c	568	547 b	21	583	598 a	-15
Sorghum sudangrass	1.43	1.43	279	244 a,b	35a	568	636 a	-68	583	545 b	38
Fallow	1.43	1.42	279	290 a	-11d	568	518 b	49	583	616 a	-32
Low rainfall rate=5.8 mm day ⁻¹											
0–10 cm											
Sunn hemp	1.43	1.34	279	204 a	75 b	568	613 a	-45	583	521 b	63
Velvetbean	1.43	1.34	279	192 a,b	87 a,b	568	597 a,b	-30	583	553 b	30
Cowpea	1.43	1.34	279	189 a,b	90 a	568	583 b	-15	583	568 a,b	16
Sorghum sudangrass	1.43	1.34	279	206 a	73 b	568	630 a	-62	583	506 b	78
Fallow	1.43	1.34	279	164 b	115 a	568	601 a,b	-33	583	580 a	4
10–20 cm											
Sunn hemp	1.43	1.42	279	260 b	19 a	568	644 a	-76	583	540 a,b	43
Velvetbean	1.43	1.42	279	290 a,b	-11 c	568	575 b	-8	583	536 a,b	47
Cowpea	1.43	1.42	279	306 a	-27 c	568	543 b	24	583	520 b	63
Sorghum sudangrass	1.43	1.43	279	276 b	3 b	568	609 a,b	-41	583	550 a	33
Fallow	1.43	1.42	279	318a	-39c	568	497b	71	583	543ab	40
ANOVA ($P \geq F$)											
Layer of soil profile			3.66*			2.87*			2.32 ^{NS}		
Rainfall (R)			4.12*			2.39*			2.65*		
Cover crop (C)			2.13*			1.88*			1.76*		
R × C			0.91 ^{NS}			1.71 ^{NS}			1.12 ^{NS}		

Values followed by same letters within the same column by rainfall rate and by depth represent no significant differences (0.05)

* $p=0.05$, significant

NS not significant

Transport of clay and silt contents was significantly influenced by cover crops, and there was no significant interaction effect between the rainfall rate and cover crop.

Under both rainfall rates in the 0–10 cm depth of soil, the clay content after (A) grown with cover crops was greater in the soil with sunn hemp and sorghum sudangrass cover crops as compared to that in the fallow treatment. In the 10–20 cm depth of soil, clay content (A) was greater in the fallow treatment as compared to that in the sunn hemp treatment at the high rainfall rate, and in both sunn hemp and sorghum sudangrass treatments at the low rainfall rate. Silt fraction was greater at 10–20 cm depth in the soil grown with sunn hemp, velvetbean, and sorghum sudangrass than that with fallow and cowpea at the high rainfall rate. At the low rainfall rate, silt fraction was greater in the soil grown with sunn hemp as compared to that in the rest of treatments. After completion of leaching, at both rainfall rates, the amount of clay in the 0–10 cm depth was greater by 25–27% in the soil grown with sunn hemp and sorghum sudangrass as compared to the fallow treatment. Similarly, the silt content at 10–20 cm depth was greater by 22–28% in the former than that in the later treatments. Sand content at 0–10 cm depth was greater in the fallow treatment as compared to that in the sunn hemp treatment under both rainfall rates. The above results support that sunn hemp and sorghum sudangrass were the most effective cover crops for reducing the transport of clay and silt fractions down the soil profile.

Transport of clay and silt fractions down the soil profile will also contribute to the transport of organic matter. The organic matter contents in the Krome gravelly loam soil were

6.0%, 4.3%, and 0.6% in clay, silt, and sand fractions by wet sieving (Six et al. 2000; Plante et al. 2006; Causarano et al. 2008) and determined by modified weight loss on ignition (Wang et al. 2010). Therefore, growing sunn hemp and sorghum sudangrass increased soil organic carbon by 5.4–6.6% as compared to that of the fallow treatment (Table 4). Initially, the soil consisted of 195.2 gkg⁻¹ clay, 397.2 gkg⁻¹ silt, and 407.6 gkg⁻¹ sand and the average soil bulk density was 1.43 gcm⁻³ through 0–30 cm soil profile. Given that 58% of the soil organic matter is organic carbon (Bowman 1998; Wang and Anderson 1998), the estimated amount of organic carbon was equivalent to 50×10³ kg ha⁻¹ in these three layers. As compared to the initial organic carbon amount of 50×10³ kg ha⁻¹, about 2–3×10³ kg ha⁻¹ of total organic carbon was migrated below 20 cm of soil profile with the fallow treatment under low and high rainfall rates.

The root mass and total plant biomass of sunn hemp and sorghum sudangrass appear to contribute to minimize leach of fine soil particles from the top soil profile as compared to that of the other cover crops evaluated in this study. Sunn hemp produced the greatest quantities of aboveground biomass associated with a large amount of belowground biomass, which might play a critical role to retain soil fine particles from leaching. The total amount of biomass was relatively low for sorghum sudangrass but it has an extensive fibrous roots distributed in the soil profile, which might be a main mechanism for sorghum sudangrass to prevent fine soil particles from leaching. In addition, the proportion of roots may also play a critical role in retaining

Table 4 Budget estimation on total amounts of soil organic matter/carbon with different fractions of soil particle for various cover crops under low and high rainfall rates at 0–20 cm depth

Rainfall rate and cover crops	Quantities of organic matter in different fractions (×1,000 kg ha ⁻¹)				Total amount of organic carbon (OC) (×1,000 kg ha ⁻¹)	Increase in OC over fallow%
	Clay	Silt	Sand	Total		
High rainfall rate (11.6 mm day ⁻¹)						
Sunn hemp	25 a	55 a	6.3 b	87 a	50 a	6.6
Velvetbean	26 a	51 a,b	6.8 a,b	84 a,b	49 a,b	3.5
Cowpea	27 a	49 b	7.1 a	83 b	48 a,b	1.5
Sorghum sudangrass	26 a	54 a	6.5 b	86 a	50 a	5.6
Fallow	26 a	48 b	7.3 a	82 b	47 b	0.0
Low rainfall rate (5.8 mm day ⁻¹)						
Sunn hemp	28 a	54 a	6.4 a,b	88 a	51 a	5.4
Velvetbean	29 a	50 a,b	6.5 a,b	86 a,b	50 a,b	3.3
Cowpea	30 a	48 b	6.5 a	85 a,b	49 a,b	2.3
Sorghum sudangrass	29 a	53 a	6.3 b	89 a	51 a	6.1
Fallow	29 a	47 b	6.7 a	83 b	48 b	0.0

The quantity of soil organic matter in each fraction was calculated by integrating the total weight of respective fraction in the corresponding depth of soil with its organic matter concentration: clay, 6.0%; silt, 4.3%; and sand, 0.6% determined by weight loss on ignition

Values followed by same letters within the same column by rainfall rate represent no significant difference (0.05)

Soil total organic carbon=soil total organic matter×0.58 (soil organic matter consists of 58% of organic carbon)

soil fine particles because sunn hemp and sorghum sudangrass had more root biomass (21.1% and 8.7%) than cowpea (4.2%) from a previous report (Wang et al. 2005).

Under field conditions, another important feature for both sunn hemp and sorghum sudangrass in reducing nutrient leaching and the downward migration of soil fine particles might be a stemflow formed by the particular architecture of their stems and leaves. Both of sunn hemp and sorghum sudangrass grew as tall as 2.5 m (in contrast to vine type velvetbean and cowpea with only 0.3–0.5 m tall) in this experiment and their leaves with an appropriate angle form a stemflow by intercepting raindrops and reducing their energy by flowing toward the plant stems and gently down to their extensive root anchored areas. The stemflow occurs often on agricultural crops, such as corn (*Zea mays*), sorghum (*Sorghum bicolor*), and many other crops (Bui and Box 1992; Levia and Frost 2003).

4 Conclusion

Leaching of N, P, and fine soil particles from a gravelly loam soil was evaluated under two simulated rainfall rates and with different summer cover crops vs. fallow condition. Growing sunn hemp and sorghum sudangrass minimized leaching of soil fine particles associated with soil organic carbon from the top soil as compared to that in a fallow soil. Sunn hemp and velvetbean facilitated increasing use of soil water and available N and P. The quantities of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and ortho-P leached from the soil profile were greater at the high than that at the low rainfall rate. Most cover crops evaluated in this study reduced N and P leaching under low rainfall rate as compared to that under fallow. However, under high rainfall rate, as typically exists in the subtropics, the $\text{NO}_3\text{-N}$ concentration in leachate from cowpea cover crop treatment was significantly greater than that for other crops or the fallow treatment. Sunn hemp and velvetbean produced much greater amounts of biomass, along with greater reduction in water and nutrient leaching from the root zone as compared to the other cover crops. In addition, long-term growing and incorporation of cover crops can improve carbon sequestration, soil fertility, and the productivity. However, much attention must be paid to the comprehensive management of soil and cropping systems because the continuous accumulation of soil nutrients may cause high nutrient leaching. Thus, inclusion of cover crops with optimum management of soil, water, and cropping systems will benefit the development of sustainable agriculture and the ecoenvironmental systems in tropical and subtropical regions.

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