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Corn Stover Removal Responses on Soil Test P and K Levels in Coastal Plain Ultisols

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Abstract: Corn (*Zea mays* L.) stover is used as a biofuel feedstock in the U.S. Selection of stover harvest rates for soils is problematic, however, because excessive stover removal may have consequences on plant available P and K concentrations. Our objective was to quantify stover harvest impacts on topsoil P and K contents in the southeastern U.S. Coastal Plain Ultisols. Five stover harvest rates (0, 25, 50, 75 and 100% by wt) were removed for five years from replicated plots. Grain and stover mass with P and K concentration data were used to calculate nutrient removal. Mehlich 1 (M1)-extractable P and K concentrations were used to monitor changes within the soils. Grain alone removed 13–15 kg ha^{-1} P and 15–18 kg ha^{-1} K each year, resulting in a cumulative removal of 70 and 85 kg ha^{-1} or 77 and 37% of the P and K fertilizer application, respectively. Harvesting stover increased nutrient removal such that when combined with grain removed, a cumulative total of 95% of the applied P and 126% of fertilizer K were taken away. This caused M1 P and K levels to decline significantly in the first year and even with annual fertilization to remain relatively static thereafter. For these Ultisols, we conclude that P and K fertilizer recommendations should be fine-tuned for P and K removed with grain and stover harvesting and that stover harvest of >50% by weight will significantly decrease soil test M1 P and K contents.

Keywords: cellulosic biomass; corn stover harvest; nutrient budget; plant available phosphorus (P) and potassium (K); Ultisols

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1. Introduction

Harvesting corn stover (cobs, stems, leaves, and husks) following grain harvest for use as cellulosic feedstock to produce bioenergy or other bio-based products has received considerable attention for the past twenty years. Recognized as a countermeasure to help mitigate increasing atmospheric CO_2 concentrations [1,2] and to off-set ever-growing global consumption of petroleum [3] for liquid fuels, sustainability of harvesting stover has been extensively studied. Ethanol and other organic alcohols (i.e., butanol, etc.) can be created by processing corn grain, sugarcane (*Saccharum officinarum*), algae and various other lignocellulosic feedstocks [4,5]. Alternatively, gas, liquid, and solid fuel phase forms of bioenergy can be produced from biomass using thermochemical conversion platforms such as co-firing, gasification, and both slow and fast pyrolysis [6,7].

With nearly 40 million hectares of corn production in the U.S., stover is one of the most abundant potential lignocellulosic feedstocks for biorefineries [8–10]. For 2020, dry biomass production was projected by the US-DOE [11] as being between 22 and 110 Mg (24 and 122 million tons). However, even though it appears that there is a large amount of corn biomass available for biofuel production, there are several ecosystem services (protection against erosion, reducing evaporation, providing a carbon food source for microbes) and uses (animal feed and bedding) for this resource. Therefore, questions have arisen as to the sustainability of stover harvest [12], with one being its impact on soil fertility and long-term crop yield [13–15].

Determining sustainable corn stover removal levels is critical for maintaining soil fertility, physical properties, and subsequent crop yields [15]. However, establishing sustainable rates is challenging, as reflected by mixed relationships reported for harvest rate, crop yield, soil fertility and other site-specific characteristics. For example, Blanco-Canqui and Lal [16,17] reported that >25% crop residue removal caused declines in subsequent grain yields. Conversely, Birrell et al. [18] reported few effects on soil quality characteristics and crop yield after four years of various stover removal treatments, while other studies showed that 50% removal had little effect on succeeding crop productivity [19,20].

Soil fertility declines due to increased plant nutrient removal associated with harvesting corn stover have been reported [10,13,21]. Karlen et al. [22] reported that compared to harvesting only the grain, removing an average of 3.9 Mg ha^{-1} of corn stover increased P and K removal by 2.7 and 31 kg ha^{-1}, respectively, while removing an average of 7.2 Mg ha^{-1}, increased P and K removal to 5.5 and 62 kg ha^{-1}. Those removals are in addition to an average of 25 to 33 kg ha^{-1} of P and K, respectively, removed by the grain [23]. Failure to account for both grain and stover nutrient removal (especially for P and K) can result in essential plant nutrient deficiencies as measured through soil testing. Both removal paths are also needed to compute plant nutrient budgets [24–26].

The impacts of crop residue removal on soil and plant nutrient measurements at the long-term research site [27] near where this study was conducted, were first quantified nearly 40 years ago [28]. Following publication of the Billion Ton Report [8] by the DOE and USDA, Karlen [28] coordinated a large-scale study to evaluate the dynamics of harvesting crop residue as feedstock for biofuels and/or bio-products. A consortium of soil scientists, agronomists, and engineers from several USDA-ARS locations, Land Grant Universities, and other federal agencies was assembled and directed to assess long-term sustainability of corn stover harvest, including its impact on soil quality (soil health) characteristics [29]. The multilocation, trans-disciplinary team quantified effects of various stover harvest rates on subsequent crop yield and several important soil quality indicators including soil test P and K. Several ARS and university locations conducted a coordinated 5 year field (2008 through 2012) experiment to assess effects of removing no, low, moderate, or high amounts of corn stover following grain harvest in seven different states (IA, IL, IN, MN, NE, PA, and SC). The locations encompassed corn production practices typical of the Midwest, Northeast, and Southeastern regions of the U.S. An overall summary of yield and nutrient removal [22] and journal articles on various sustainability indicators [10] have been published, but detailed, site-specific assessments such as changes in soil test P and K concentrations or topsoil mass balances have not been reported for several of the locations including the site reported upon herein. The objectives, therefore, are to: (i) determine topsoil (0 to 15 cm) P and K mass balance response to five stover harvest rates (0, 25, 50, 75 and 100% of above-ground biomass from continuous corn plots, and (ii) evaluate changes in M1-extractable P and K concentrations in topsoil of toposequential Coastal Plain Ultisols.

2. Methods and Materials

2.1. Site Description and Experimental Setup

This field study was conducted at 34°17′18.5″ N, 79°44′16.3″ W on the Clemson University, Pee Dee Research and Education Center near Florence, SC. Twenty, 138 m^2 plots were established using a randomized complete block design with each plot accommodating 12 of 15 m corn rows spaced 0.76 m apart. Plot size was selected to ensure the combine had sufficient time and travel distance to shell ears and eject stover.

Soil series mapped with each transect areas were classified as Ultisols and were representative of the Goldsboro–Lynchburg–Coxville/Rains toposequence. Geologically, the soils were formed between 0.5 and 5 million years BCE in loamy marine sediments or fluvio-marine sediments deposited within the Middle Coastal Plain physiographic region [30]. These soils are commonly found throughout the South Carolina Coastal Plain and have historically been used for agricultural crop production [31,32].

Daily rainfall was measured at the Pee Dee Weather Station Site no. 2037 (34°18′ N and 79°44′ W) in Darlington County, SC for 2008 through 2012. The complete weather record is available through the USDA-NRCS National Water and Climate Center (https://wcc.sc.egov/nwcc/site?sitenum=2037&state=SC, accessed on 14 April 2021).

Tillage, agronomic and fertilizer management practices were typical for corn production in the South Carolina Coastal Plain region (Table 1). Prior to planting, fertilizer recommendations were determined by sampling soils in March of each year.

Table 1. Agronomic management practices.

	Fertilizer Applied (kg ha^{-1})				Planting Rate
Year	**N**	**P**	**K**	**Corn Cultivar**	**Plants ha^{-1}**
2008	140	0	0	DeKalb C69-71	49,505
2009	140	20	50	DeKalb C69-71	49,505
2010	140	20	50	DeKalb C69-71	54,455
2011	99	17	42	DeKalb C69-71	54,340
2012	135	34	83	DeKalb C69-71	54,450

A final soil sampling was taken in March 2013 to compute a topsoil mass balance reflecting P and K additions and removals throughout the project. Eight, 2.5 cm diameter soil cores were randomly collected from each plot to a depth of 15 cm. Samples were composited, air-dried, and analyzed for routine soil test parameters using M1 extraction at Clemson University's Soil Testing Laboratory (https://www.clemson.edu/public/regulatory/ag-srvc-lab/index.html, accessed on 14 April 2021). To convert concentration units of mass, soil bulk density samples were collected from the same depth increments using the core method described by [33].

Annual fertilizer application rates and plant populations are shown in Table 1. For N, liquid urea ammonium nitrate (UAN) was split applied at planting and the V6 corn growth stage, while except for 2008, granular P and K were applied annually in March. A 6-row, John Deere MaxEmerge XP no-till planter, attached to a Kelly Manufacturing Company (KMC) in-row subsoiler, was used to plant Dekalb C69-71 hybrid corn (a 114 day relativity maturity variety with an intermediate FAO mature date of 300–399). The seeding rate was 49,505 and 54,455 plants ha^{-1} in 0.76 m wide rows in mid-April of each year (Table 1). The in-row subsoiler, mounted in front of each planting coulter, is designed to disrupt a root-limiting hard pan (E horizon) at a depth of approximately 40 cm [34].

Corn stover (all above-ground plant parts, excluding grain) was collected from each plot using a "diaper method" that consisted of a canvas tarp mounted to the back of a commercial combine. This enabled us to collect 100% of the material passing through the machine. The wet corn stover captured by the canvas tarp was weighed in the field, and subsamples were taken for over drying and moisture content determined by weight. Knowing the total amount of corn stover collected for each plot, fractions representing 0, 25, 50, 75, and 100% on a wet weight basis were manually spread to establish specific removal rates for each plot. After determining stover moisture content, the wet stover weights were corrected to a dry weight basis for final reporting. The stover was spread by hand as uniformly as possible across each plot. Corn grain yield was determined by weighting the corn grain from each plot in a scale-equipped wagon. While transferring grain from the combine to the wagon, a sample was collected to determine moisture content and nutrient concentrations from which marketable yield and nutrient removal were calculated.

2.2. Corn Grain and Stover Analysis

Grain and stover samples were analyzed for total P and K using ICP analysis after wet digestion [35] at the Clemson University Plant Testing Laboratory (https://www.clemson.edu/public/regulatory/ag-srvc-lab/index.html, accessed on 14 April 2021). Concentrations for both nutrients were multiplied by harvest mass to quantify total P and K removal from each plot via grain or stover. Total P and K removal through grain harvest alone or grain plus any of the stover harvest treatments were computed by summing annual removal amounts (Table 2). Net mass balance changes were computed by subtracting total P and K removal annually and for the entire five years from amounts applied a fertilizer (Table 1). The differences between P and K removed/returned was determined and results expressed with a negative value indicate more P and K nutrients were removed in corn grain and stover than was replaced with inorganic fertilizer addition and as returned stover. Mehlich 1 P and K concentrations were determined by depth and year for each treatment and expressed as kg ha^{-1} after conversion using associate soil bulk density values.

Table 2. Annual mean corn stover (minus grain weight) removed and returned to plots (% stover removed on a dry weight basis).

Stover Removed (%)	Annual Mean Corn Stover (kg ha^{-1})		
	Year	Removed	Returned
0	2008	0	6712
	2009	0	8543
	2010	0	6676
	2011	0	4274
	2012	0	7996
	mean	0	6820
25	2008	1657	4970
	2009	1919	5758
	2010	1624	4871
	2011	1138	3415
	2012	1754	5263
	mean	1618	4851
50	2008	3196	3197
	2009	4056	4056
	2010	3107	3107
	2011	2393	2393
	2012	3924	3924
	mean	3335	3335
75	2008	4814	1618
	2009	5839	1947
	2010	5081	1693
	2011	3528	1176
	2012	5944	1981
	mean	5041	1683
100	2008	6408	0
	2009	8295	0
	2010	6494	0
	2011	4931	0
	2012	7508	0
	mean	6757	0

2.3. Statistical Analysis

Nutrient removal by grain or grain plus a fraction of the stover and soil test P and K values were analyzed using an ANOVA with SigmaPlot v. 13.0 (SYSTAT Software, San Jose, CA, USA) software. For this ANOVA, experimental years were used as treatment replicates.

3. Results and Discussion

3.1. Agronomic Practices

Throughout the 5 year study, inorganic fertilizer was provided to all plots at rates from 99 to 140, 0 to 34, and 0 to 83 kg ha^{-1}, for N, P, and K, respectively (Table 1). Baseline extractable P and K in 2008 indicated P and K were sufficient for Coastal Plain non-irrigated corn production, so only N was applied. Thereafter (2009–2011), modest amounts of P and K were applied, but decreasing soil test values resulted in application rates for these essential plant nutrients being nearly double in 2012 (Table 1). Meanwhile, planting rates which for the first two years were <50,000 plants ha^{-1} were increased ~10% to an average of 54,500 plants ha^{-1} to better align with higher corn populations in the SC Coastal Plain (J.R. Frederick, Personnel Communication, Clemson University, 2010).

3.2. Stover Harvest Rates

Annual stover removed and returned are presented in Table 2. For all five treatments, total above-ground mean corn stover removed from the plots ranged from 1618 to 6757 kg ha^{-1}. Overall aerial biomass production for the 0% removal treatment was similar to that reported by [36,37]. Those two studies reported corn stover production from 7683 to 8350 and 5934 to 9340 kg ha^{-1}, respectively, for studies with multiple years of corn grown on pedogenically similar Ultisols (i.e., Goldsboro, Norfolk, Rains series) with similar agronomic practices.

3.3. Grain and Stover P and K Concentrations and Removal

Corn grain from the various stover harvest treatments removed an average of 13 to 15 kg ha^{-1} of P and 15 to 18 kg ha^{-1} of K each year (Table 3). Cumulative P and K removal by grain alone, was 70 to 85 kg ha^{-1}, respectively, for the five stover removal treatments. A simple mass balance shows those removal quantities accounted for 77% of the collective P and 38% of the K applied as fertilizer (i.e., 91 and 225 kg of P and K: Table 1). Removing 25, 50, 75, or 100% of the above-ground biomass (i.e., stover), respectively, resulted in an average P removal of 2, 4, 5 and 6 kg ha^{-1} (Table 3). Similar calculations for K show that stover harvest alone increased average annual removal by 20, 40, 60 and 79 kg ha^{-1}, respectively. Again, adding stover and grain removal together, the cumulative K removal increases to 37, 55, 78, and 97 kg ha^{-1}, or 16, 24, 34, and 43% of the total K fertilizer application ($\sum$225 kg K; 2008 to 2012). These P and K removals are similar to those reported by Karlen [28] for what they defined as moderate (~50%) and high (~90%) harvest rates. These results suggest that harvesting grain and stover from Coastal Plain soils will require a reevaluation of fertilizer recommendations since their combined nutrient removal totals caused a lowering of M1-extractable P and K concentrations (see next section). This is a salient finding because P and K availability is a concern in the highly weathered Ultisols in the South Carolina Coastal Plain region [38]. These soils are inherently nutrient poor and have a poor ability to store nutrients because of low cation exchange capacities, low organic matter contents and sandy soil textures [39].

Results from Table 3 along with K and P fertilizer addition (Table 1) were used to calculate annual K and P mass balance estimates for each treatment system (Table 4). Overall, removal of 0, 25 and 50% corn stover resulted, for the most part, in positive mass balance K and P values (Table 4). The positive values indicated that K and P were being resupplied to these three treatments. However, the amount of K and P returned were declining with increasing residue removal. The mass balance calculations revealed that removal of 75% corn stover caused corresponding M1 P and K topsoil reductions of −0.4 to −12.5 kg ha^{-1}, respectively, while 100% removal increased M1 P and K losses to −2.6 to

−51.2 kg ha^{-1} (Table 4). Statistical analyses revealed that the P and K removed at stover harvest amounts of >50% were significantly different than corresponding nutrients removal at the lower amounts (<50%).

Table 3. Mean phosphorus (P) and potassium (K) contents in corn grain and removed/returned under variable corn stover removal amounts (standard deviations in parentheses).

	% Corn Stover Removed (kg ha^{-1}) †				
Nutrients in Corn Grain	**0**	**25**	**50**	**75**	**100**
P	14 (7) a	14 (6) a	13 (6) a	15 (7) a	14 (6) a
K	17 (9) a	17 (7) a	15 (7) a	18 (7) a	18 (7) a
Stover P					
removed	0 (0) a	2 (0) b	4 (1) c	5 (1) cd	6 (2) d
returned	8 (2) a	6 (1) b	4 (1) c	2 (0.5) d	0 (0) e
Stover K					
removed	0 (0) a	20 (5) b	40 (10) c	60 (15) d	79 (17) e
returned	84 (22) a	61 (14) b	40 (10) c	20 (5) d	0 (0) e

† Means between columns followed by a different letter are significantly different using an ANOVA at $p = 0.05$ level of significance.

Table 4. Mean phosphorus (P) and potassium (K) mass balances from treatments under variable corn stover removal amounts (a negative value indicates more nutrient removed in corn grain and stover than replacement with inorganic fertilizer and returned corn stover; standard deviation in parentheses).

	Nutrient Mass Balance (kg ha^{-1}) Estimate for Each % Stover Removal Amount †				
Nutrient	**0**	**25**	**50**	**75**	**100**
P	12.6 (11.9) a	8.4 (11.5) a	5.5 (11.6) a	−0.4 (12.6) a	−2.5 (11.7) a
K	116.5 (51.6) a	68.9 (35) ac	30.1 (28.4) bc	−12.5 (25) bd	−51.2 (25.3) d

† Means between columns followed by a different letter are significantly different using an ANOVA at $p = 0.05$.

3.4. Soil Test P and K

One potential soil fertility repercussion of removing too much crop residue for biofuels, bio-products, or any other use is nutrient depletion [38,40]. Preventing depletion of essential plant nutrients in crop/biofuel production systems is the cornerstone for a well-managed soil fertility program. To maintain an appropriate nutrient balance, soil testing methods have been developed and nutrients exported from the field are typically replaced by adding animal manure and/or fertilizers [40,41]. Having quantified P and K removal in both grain and stover provided an excellent opportunity to evaluate not only effects of biomass removal, but also soil test sensitivity and fertilizer recommendations and nutrient use efficiencies.

The impact of various corn stover harvest rates on M1-extractable P and K in topsoil (0–15 cm depth) is presented for 2008 through 2013 in Figures 1 and 2. Grain harvest alone (i.e., no stover removal) as well as the four stover harvest treatments showed significant decreases in extractable P and K, especially by 2010. When fertilizer rates were increased (e.g., P applied in 2009 and 2011; K in 2011; Table 1), soil test values rose slightly, but not to original, pre-study levels (2008).

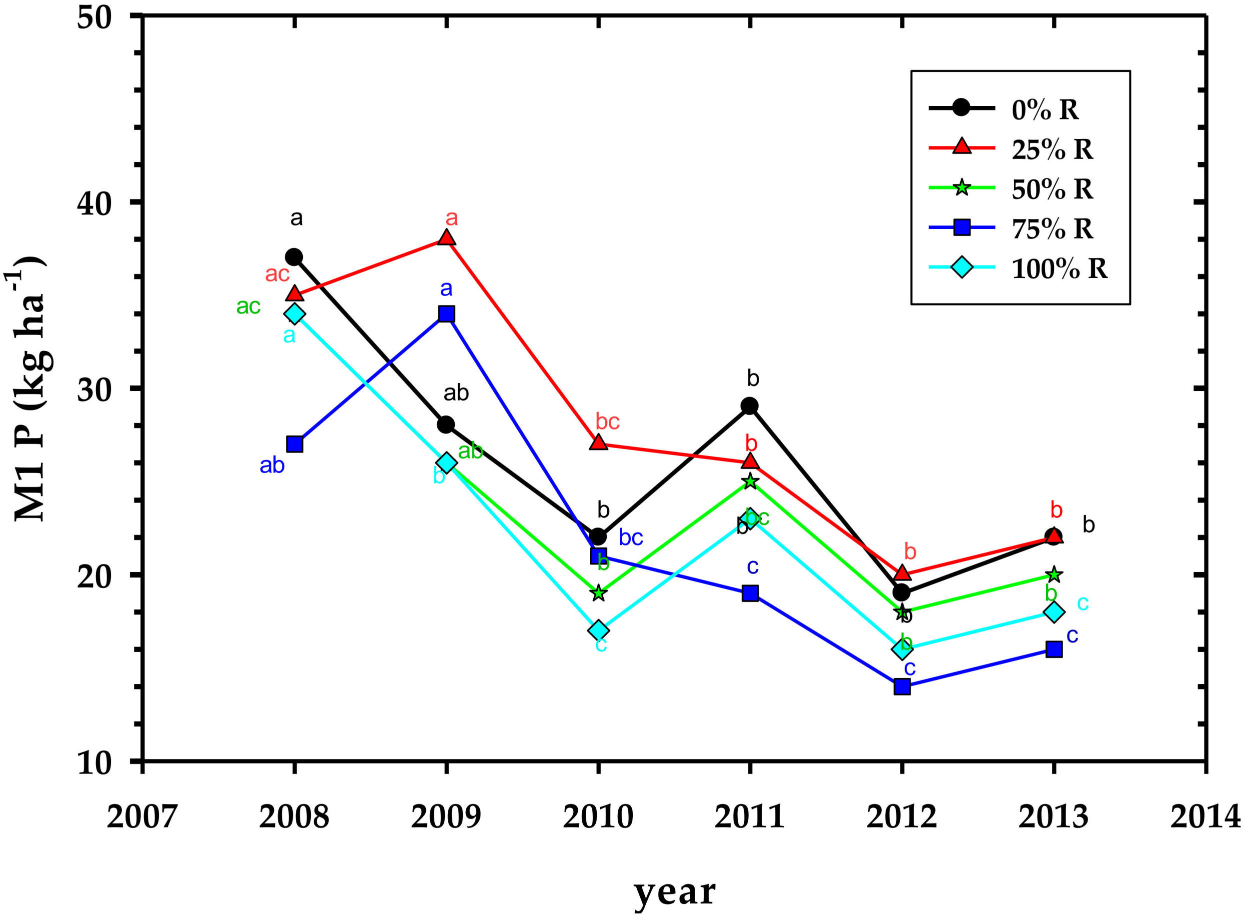

Figure 1. Annual mean topsoil Mehlich 1 (M1) phosphorus (P) concentrations versus percentage of dry corn stover removal (R, means followed by a different letter are significantly different using an ANOVA at $p = 0.05$ level of significance.

Mehlich 1-extractable concentrations of both nutrients showed significant decreases with P concentrations decreasing significantly by 2010 and K concentrations dropping significantly between 2008 and 2009 for stover harvest treatments (Figures 1 and 2). Soil test P and K concentrations continued to decline in subsequent years with the largest drop being in the 75 to 100% stover harvests. This is consistent with the P and K mass balance estimates (Table 4).

Failure to apply K fertilizer in 2008 resulted in a significant reduction in topsoil K concentration in just one year (Figure 2). Applying K fertilizer thereafter did not appreciably increase K concentrations, and in fact, they remained fairly static. By 2013, all treatments had soil test P and K concentrations much less than when the study started (2008). It is interesting that by 2013, all treatments had very similar mean topsoil K concentrations (Figure 2; 42 to 53 kg ha^{-1}), irrespective of the amount of K removed in stover and grain or applied as fertilizer. In retrospect, the significant decline in M1 soil K between 2008 and 2009 emphasizes that attention must be given to managing K even though it does not have the potential negative environmental impacts that either N or P can have. Fertilizer replacement of K must equal or exceed the amount being removed rather than assuming traditional maintenance fertilization practices will be sufficient to maintain soil K levels throughout the profile. In spite of the noted declines, the corn plant were probably meeting their K demand by extracting available K from deeper profile depths, since this cation is known to leach from sandy-textured, low organic matter top soils [42,43] until it eventually accumulates in clay-enriched subsoil horizons [44].

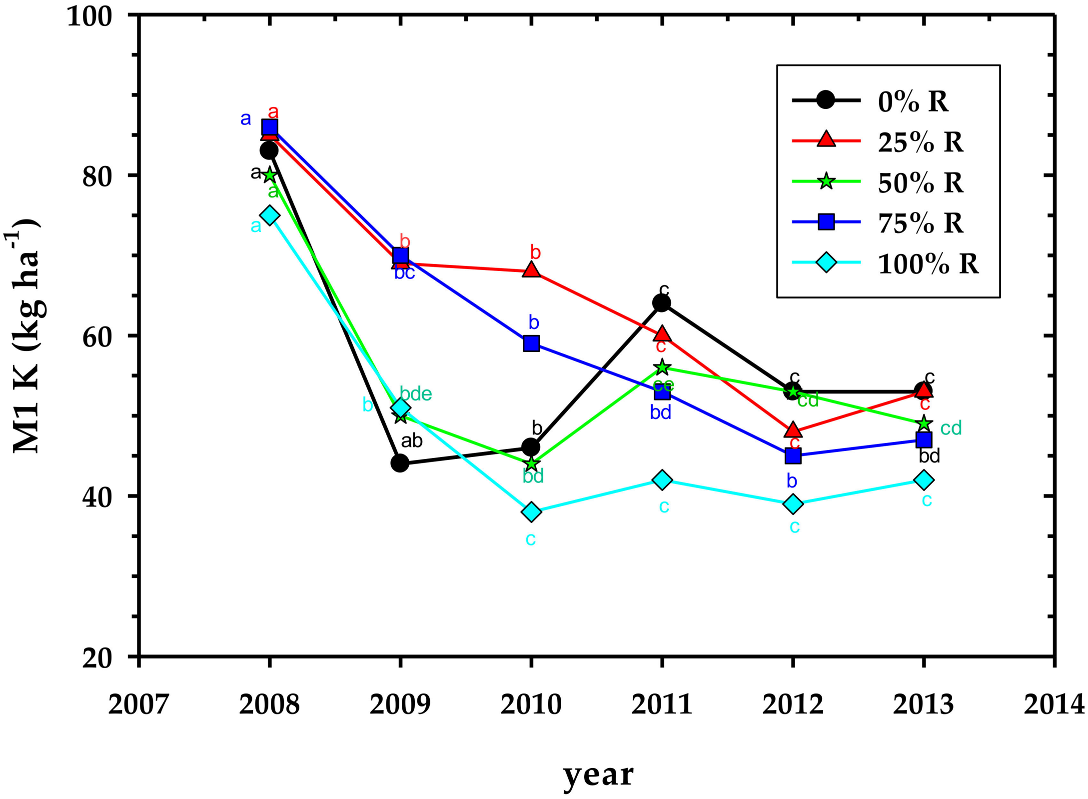

Figure 2. Annual mean topsoil Mehlich 1 (M1) potassium (K) concentrations versus percentage of dry corn stover removal (R, means followed by a different letter are significantly different using an ANOVA at $p = 0.05$ level of significance).

Some similar trends in M1-extractable P were also noted (Figure 1). Grain and stover harvest alone significantly decreased M1-extractable P when compared between 2008 and 2010, but thereafter mean P concentrations between years were similar (Figure 1). The need for additional annual P fertilizer applications was verified by decreases of 11 to 16 kg ha^{-1} M1-extractable P between 2008 and 2013 for all treatments (Figure 1). Fertilizer P was applied in 2009 through 2012 (Table 1), but the cumulative amount (91 kg ha^{-1}) was not sufficient to return M1 P concentrations to baseline (i.e., 2008) levels. These results strongly suggest that P fertilizer recommendations for corn production on Coastal Plain soils need to be re-evaluated, since depletion occurred not only in stover harvest treatments, but also when only grain was harvested (i.e., 0% corn stover harvest treatments).

4. Summary and Conclusions

Research evaluating corn stover harvest for biofuel production has been a cyclic quest for over forty years, yet stakeholders still requested information on sustainable harvest levels to prevent soil quality degradation [45]. This information is especially germane for sustainable biofuel production using stover harvested from corn grown in nutrient-impoverish sandy Coastal Plain South Carolina Ultisols. Thus, this study focused on changes in M1-extractable P and K concentrations as affected by grain and stover harvest amounts. Removing between 0 and 100% corn stover for five years from these sandy Ultisols increased P and K removal by 2 to 6 and 20 to 79 kg ha^{-1}, compared to grain-only harvest. Significant reductions of M1 P and K concentrations were most evident after removal of >50% stover by weight. The substantial decrease in M1-extractable P and K concentrations suggests that fertilizer recommendations for corn stover harvesting in these Ultisols should be re-evaluated. This re-evaluation could include increasing P and K fertilizer applications to the Ultisols to maintain current ex-ante levels or as direct replacement at commensurate levels with that removed by grain and stover harvest. We forecast that this information will be useful for biofuel producers considering maintaining sustainable corn stover removal rates and for modelers determining economic costs for biofuel processing.

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