Phosphorus runoff from no-till soils - do cover crops make it better or worse?

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Abstract

The goal of the proposed research is to provide data on how a range of cover crop practices impact the loss of phosphorus by surface runoff. We will investigate several mechanisms by which cover crops can affect the loss of phosphorus. Cover crops may 1. Reduce the volume of runoff water from a storm. 2. Increase the amount of rain required to start runoff from fields. 3. Reduce the concentration of P-carrying sediment in runoff water or 4. Increase the concentration P dissolved in runoff water. Phosphorus reduction might occur by uptake by the plants and phosphorus increase might occur by freezing injury that releases soluble phosphorus from cover crop tissues. Research has already been published that compares the solubility of phosphorus in live and dead tissues from a wide range of cover crop species. What is lacking, and our research will provide, is data that shows the actual runoff volume and P concentration from single species or multi-species cover crops on soils under no-till management. The current project aims to generate this data from research plots and farm fields using simulated and natural rain events during the cover crop season.

Background

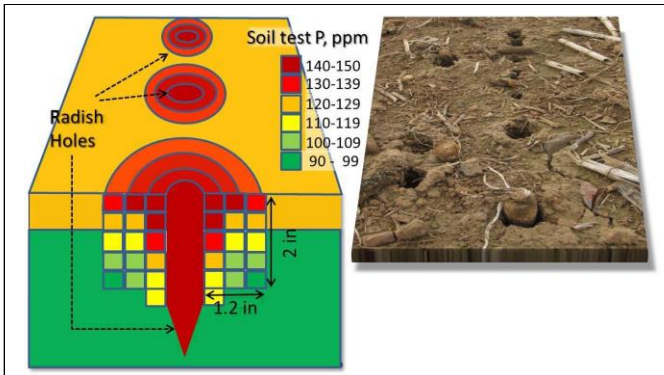

Figure 1 Concentration of soil test P near soil surface and radish root holes in spring after winter-killed forage radish cover crop. White and Weil, 2011.

While cover crops can provide many benefits to the farmer, the Maryland cover crop program is primarily focused on the reduction of nitrogen loading to the Chesapeake Bay. The main pathway for nitrogen losses from farm fields is via groundwater contaminated soluble nitrogen by leaching. Research, including our work sponsored by the Maryland Soybean Board, have clearly shown that cover crops can be very effective in reducing such nitrogen leaching and that their effectiveness is dependent on early cover crop establishment in fall.

Water quality troubles in the Chesapeake Bay are related to both nitrogen and phosphorus, but much less is known about the impacts of cover crops on phosphorus losses than on nitrogen losses. The main pathway for phosphorus transport from croplands to bodies of water is via surface runoff during intense rain storms or heavy snow melt. A secondary pathway in areas of poorly drained sandy soils is leaching of phosphorus to drainage ditches. There is little research on how cover crops impact phosphorus losses. Some studies that suggests that cover crops might increase soluble phosphorus at the soil surface where it would be susceptible to becoming dissolved in runoff water. In fact, cover crops can be an important tool for increasing P availability and crop yields in the phosphorus deficient soils found in many parts of the world where there has been little application of P (Hallama et al., 2019). Cover crop mechanisms that cycle P and make soil P more soluble and plant–available may also allow high productivity on Maryland farms with lower levels P fertilization. This could be part of a long-term strategy to make farming more sustainable both economically and environmentally. The goal of the proposed research is to provide data on how a range of cover crop practices impact the loss of phosphorus by surface runoff. Cover crops can affect the loss of phosphorus by several, somewhat contradictory, mechanisms. Cover crops might:

1. Reduce the volume of runoff water from a storm.
2. Increase the amount of rain required to start runoff from fields.
3. Reduce the concentration of P-carrying sediment in runoff water.
4. Increase the concentration P dissolved in runoff water.
5. Reduce phosphorus in surface soil because of plant P uptake.
6. Increase P concentration by freezing injury that releases soluble phosphorus from cover crop tissues.

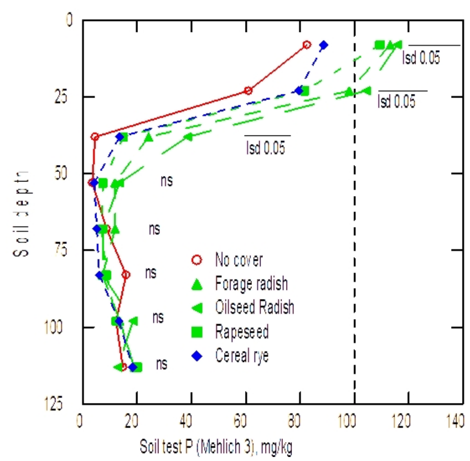

Figure 2 Soil test P stratification in no-till silt loam soil at Wye REC as amplified by three years of cover cropping. Grove, et al., 2007.

Research has already been published that compares the solubility of phosphorus in live and dead tissues from a wide range of cover crop species (Cober et al., 2018; Miller et al., 1994). Generally, freeze-thaw modestly increases the water extractability of P from tissues of winter-hardy species but dramatically increased it from freeze-susceptible annuals such as radish (Bechmann et al., 2005; Cober et al., 2018; Cober et al., 2019; Liu et al., 2013; Øgaard, 2015). Winter-killed brassica cover crops have been shown (Figure 1) to concentrate soil test extractable P at the soil surface in spring (White and Weil, 2011). Other cover crops, such as cereal rye, also have been shown to increase soil test P near the soil surface (Figure 2) in the absence of P applications, though to a lesser extent than brassicas (Grove et al., 2007).

A few studies around the world have investigated cover crop effects of P runoff, but we found none in Maryland and none using multi-species cover crops. A perennial forage vegetative cover during winter in Manitoba, Canada, resulted in more than double the soluble P and total P loads in runoff from snow melt as compared to dead annual crop residue cover (Liu et al., 2014). The increase was attributed to P dissolving out of the frost-injured green plant tissue. A study on soybeans in Missouri (Zhu et al., 1989) reported that runoff volume from erosion plots was reduced by 44 to 53% by the presence of three grass cover crops, but soluble P concentration in the runoff was increased by 161 to 286%, resulting in less runoff water but more soluble P loading from the cover cropped plots. A recent study in Iowa (on no-till Mollisols) reported that a rye cover crop, despite having only modest biomass and being planted up and down slope, reduced both runoff volume and P concentration in the runoff from a 65 mm simulated rain. The runoff was 27 mm with bare soil between corn stover and only 9.5 mm with a cereal rye cover crop. The total dissolved P concentration in the runoff water was reduced from 21 mg/L to 9.3 mg/L, thus reducing the total soluble P loss from almost 6 to less than 1 kg P/ha (Korucu et al., 2018). These values should be viewed in the context of the 0.05

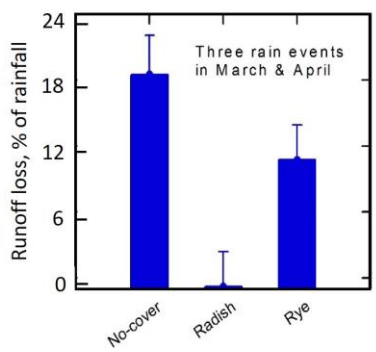

Figure 3 Cover crop effects on runoff volume from three rainfall events in early spring on a farm in central Maryland with conventionally tilled silt loam soil (Weil, unpublished)

mg/L dissolved P environmental limit for streams flowing onto lakes. Preliminary studies done by the PI some years ago, suggest that even though they released P when they winterkills, radish cover crops leave large root holes after they die that may effectively reduce runoff from moderate storms more than other cover crops (Figure 3).

Circumstantial evidence suggests that increased adoption of conservation tillage in Ohio may have increased soluble reactive P runoff loads in the Sandusky River (compared to the Maumee or Raisin Rivers) during 1998-2014 (Jarvie et al., 2017). Results from simulated rain runoff in an Indiana study suggest that cover crops did not decrease or increase soluble P loading (Smith et al., 2017). However, the project in Indiana also showed (Table 1) that incorporation P sources, such as knifed-in or surface dribbled liquid polyphosphate fertilizer, may pose a lower risk of P loss to surface water than surface applied, especially dry fertilizers (Smith et al., 2016).

From a P management perspective, different site indices and fate-and-transport models used in various parts of North America to assess risks of P loss to water have had only limited success in dealing with manure and P fertilizer, let alone cover crop effects (Kleinman et al., 2017).

Table 1 Phosphorus loss in runoff from a simulated rainfall event in Indiana as influenced by P source material and method of application (surface or incorporated). Smith et al. 2016.

Fertilizer source	Placement	P Rate kg ha^{-1}	Soluble P load mg	P loss relative to applied %
Monoammonium phosphate	Surface	112	89.3 a	17.4 a
Diammonium phosphate	Surface	127	84.6 a	16.5 a
Triple super phosphate	Surface	127	97.3 a	19.0 a
Polyammonium phosphate liquid	Surface	172	**2.1 d**	0.17 d
Single super phosphate	Surface	324	66.8 b	13.0 b
Bone meal	Surface	417	8.6 d	1.45 d
Rock phosphate	Surface	1945	3.0 d	0.37 d
Poultry litter	Surface	1459	25.5 c	4.80 c
Unfertilized control	–	–	**1.2 d**	–
Monoammonium phosphate	Banded	112	**1.8 d**	**0.13 d**
Polyphosphate liquid knifed-in	Banded	172	**1.5 d**	**0.12 d**
Poultry Litter	Banded	1459	**4.0 d**	**0.57 d**

A study (Bechmann et al., 2005) using simulated rainfall and 1 m long metal trays holding a 5 cm layer of a Pennsylvania soil with manure applied or annual ryegrass cover crop seeded reported little effect of freeze-thaw cycles on P runoff from manured or bare soils, but a very large increase from annual ryegrass (Table 2). The annual ryegrass in their study was very young (21 day after planting) and susceptible to frost damage.

In a study (Weyers et al., 2019) done in northern Minnesota with frozen soil during the winter, cover crops were drilled into wheat stubble in August and soybeans planted green into cover crops the following spring. Rye terminated by glyphosate but pennycress and winter camelina cover crops were allowed to mature for oil seed harvest as intercrop. Radish winterkill after producing ~1,200 kg/ha with 0.34% P in fall. No increase in soil porewater P (at 30 or 60 cm) nor in available soil P or soybean P uptake was observed after radish.

What is lacking, and our research will help provide, are data that show the actual runoff volume and P concentration from single species or multi-species cover crops under Maryland soil and climatic conditions. We propose to generate this data from research plots and farm fields using simulated and natural rain events during the cover crop season (October-May), and in some instances, during the summer season.

Table 2 Dissolved reactive P (DRP), total P (TP), and suspended sediments (SS) in runoff from 1 m long trays of 5 cm deep Watson soil receiving simulated rainfall and different treatments of freezing and soil management (n = 2). Standard deviation in parentheses. Bechmann et al. 2005.

Soil management	Runoff volume	DRP	TP	SS
	L / 30 min	----- mg/L	-----	g/L
		Not frozen		
Ann. ryegrass cover	3.3	0.10(0.04)	**0.49**(0.2)	0.04(0.03)
Dairy Manure	2.9	0.14(0.04)	2.02(0.7)	1.45(0.6)
Bare soil	2.7	0.09(0.02)	1.72(0.8)	1.28(0.5)
		Frozen soil		
Ann. ryegrass cover	3.2	9.7(1.6)	**17.9**(4.0)	0.59(0.3)
Dairy Manure	2.7	0.18(0.03)	3.25(0.9)	1.33(0.3)
Bare soil	2.8	0.14(0.04)	2.42(0.4)	0.96(0.2)

Preliminary results from 2018-2019 season:

In the first year of this project we established cover crop plots in a full season soybean field and installed 9 runoff weirs. The cover crop treatments were 1) no cover control, 2) 3-way mix interseeded into soybeans at leaf drop, and 3) 3-way mix drilled after soybean harvest. The slope ranged from 6 to 9% and the soil had a loamy sand surface texture. The field had a history of no-till corn-soybean rotation. Between 4 November 2018 and 23 March 2019 there were 9 rain events that produced runoff. Except for the first two events, the nitrate-N concentrations in the runoff were below the USEPA 0.3 mg/L limit for stream water. However, the dissolved phosphate –P tended to be slightly above the 0.05 USEPA limit for total dissolved P in stream water (Figure 4).

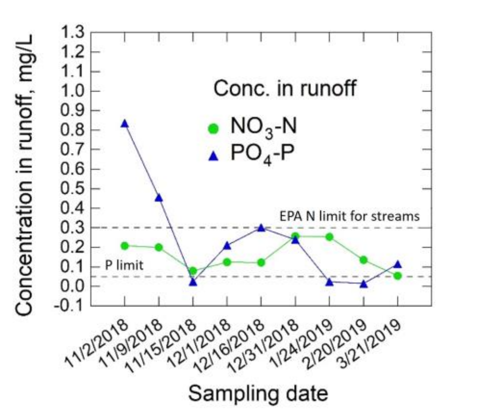

Figure 4. Concentrations of nitrate-N and phosphate-P dissolved in runoff water from cover crop plots in winter 2018-2019. Means of 3 reps and 3 cover crop treatments on sandy soil following no-till soybeans at Beltsville, MD. USEPA N and P limits from (Litke, 1999; USEPA, 2002). Data of Weil, unpublished.

The cover crop treatments did not have a significant effect on N and P concentrations in the runoff water. However, they did affect the amount of runoff water and therefore the amount of P lost per unit area of land (Figure 5).

Figure 6 shows the cumulative runoff volume, soil loss and phosphate –P loss for the entire cover crop 2018-2019 season. The inter-seeded cover crop treatment had the least soil loss and the drilled cover crop treatment had the greatest runoff volume and P losses. We ascribe these greater losses to the smaller cover crop growth due to later planting combined with the soil residue cover disturbance by the no-till drilling operation.

The runoff and sediment samples are currently being prepared and digested for total and dissolved organic P determination.

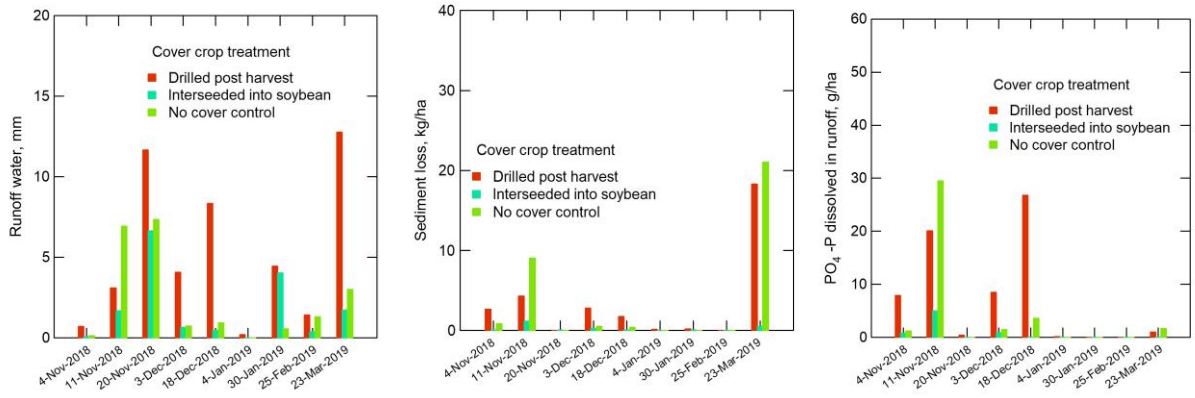

Figure 5 Runoff water volume, sediment loss and phosphate-P loss during nine runoff-producing rain events between 04 November 2018 and 23 March 2019 on sandy soil after soybeans in continuous notill corn-soybean system at Beltsville, MD.

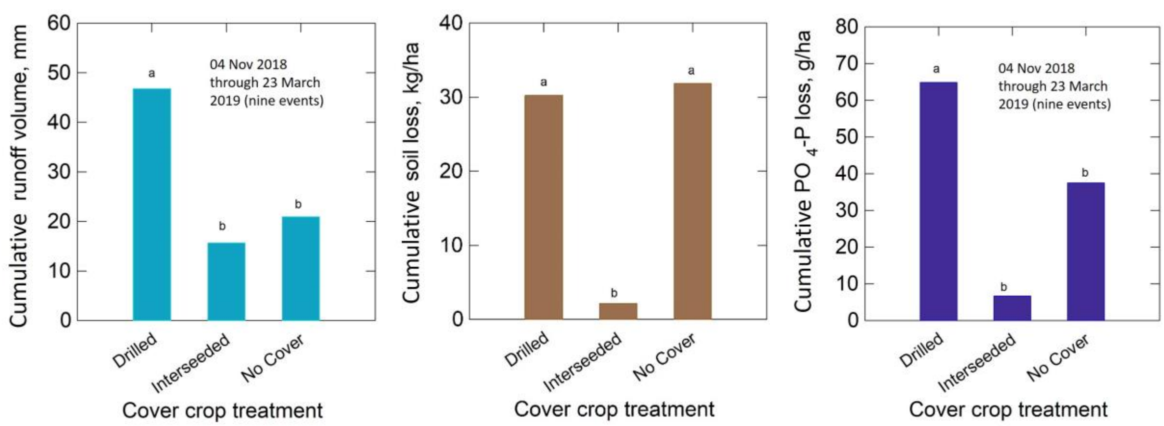

Figure 6. Cumulative runoff water volume, sediment loss and phosphate-P loss between 04 November 2018 and 23 March 2019 (nine runoff-producing rain events) on sandy soil after soybeans in continuous notill corn-soybean system at Beltsville, MD.

Research objectives for 2019-2020 Cover Crop Season:

1. Determine effect of individual species and mixed cover crop on:
   a. Runoff volume generated as percent of rainfall.
   b. Time and rain volume required to cause runoff to begin.
   c. Concentration of total and dissolved phosphorus in runoff water.
   d. Total P load lost to runoff during a single storm and all storm in a whole season.
2. Compare effect of multispecies and singe species cover crops on runoff at different times of year:
   a. Fall
   b. Winter
   c. Spring
   d. Early summer
3. Test the hypothesis that cold injury or death of frost susceptible cover crops such as radish is expected to release large amounts of phosphorus from lysed plant cells and this soluble P is likely to be evident as a dramatic increase in P concentration in runoff water after such winter-injury of cove crops.

Research approach:

<u>Cover crop treatments for 2019-2020.</u>

Cover crop plots 3 m (10 ft) wide and 30 m (100ft) long were established on two sites at the Central Maryland Research and Education Center (CMEC) Beltsville Facility. Field 25E has relatively fine textured soils (sandy loam topsoil with clay loam subsoil in the Russet Series), while Field 39A has much coarser soils (loamy sand topsoil over sandy loam subsoil in the Hammonton series). Both sites have a long history of no-till farming, mainly in a corn-wheat-double crop soybean rotation. To ensure vigorous and uniform cover cop stands, the cover crops were no-till drilled into wheat stubble on 26 August 2019. The four cover crop treatments replicated three times at each site were:

1. Cereal Rye
2. Forage radish
3. 3-species mix (Radish + rye + Crimson Clover)
4. No cover (weeds only) control treatment.

Mini erosion weirs were installed as soon as possible after the last cover crop planting date. They were intended to be left in the ground until the summer crop was planted in May 2020 but had to be removed in March due to the Covid19 lockdown restrictions. A total of four replicate erosion weirs were installed for each treatment, three replicates on the finer soil site were slopes varied from 5 to 6.5% and a fourth replicate on the coarser soil site where the slope was 4.5-5.0%. Only one replicate was installed on the coarser site because the other two replicates of the plots had slope of less than 4% and little or no runoff would be expected with so little slope on such a coarse textured soil. The percent green ground cover inside each weir was measured on five dates between October 2019 and February 2020 employing the CANOPEO smart phone app (Patrignani and Ochsner, 2015) which uses vertically taken digital images or videos (see Figure 7).

Two commercial fields with medium to high phosphorus risk soils (average soil phosphorus Fertility Index Value of > 200) on the Eastern Shore were also meant to be investigated using the portable Cornell sprinkle infiltrometer. Large scale plots of no-cover control and the same 3-way mixture were established either by aerial interseeding in early September / late August or by no-till drilling after crop harvest in late September or early October on these commercial fields. The rainfall simulation and runoff collection were planned to take place on at least two occasions (March and April--May) with 4 replicates comparing the cover cropped area to the no cover control at each field. However, these rainfall simulation activities were not possible after the Covid19 restrictions went into effect.

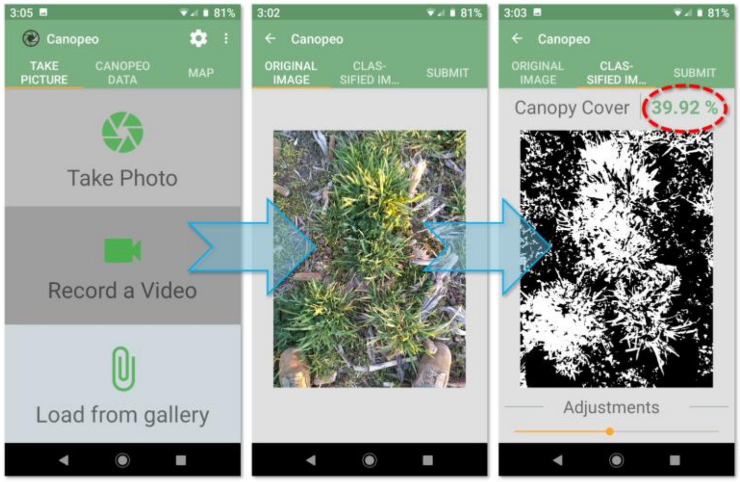

Figure 7. The CANOPEO smart phone app easily determines the percent ground covered by living vegetation.

As indicated above, this research used two main tools to measure cover crop impacts on phosphorus runoff from no-till fields. The two tools are shown in Figures 8, 9 and 10, namely semi-permanently installed mini runoff weirs and the portable Cornell rainfall simulator. Both are small-scale instruments that measure runoff as affected by field conditions. The runoff weirs are installed after the cover crop emerges in non-wheel tracked areas of representative cover crop growth since research (Kaspar et al., 2001) has shown that compaction due to wheel traffic can have a greater effect on runoff than cover crops. The big advantage of such small-scale measurements is that they can be replicated on a number of sites and treatments. The disadvantage is that they represent only the crop-soil conditions and not the whole field watershed properties. The cost to instrument a whole field water for runoff is prohibitive for this program (> $20,000 for a single watershed treatment). In the future we hope to bridge this gap in the second year of the study by installing replicated mini-weirs within one or two large, established instrumented watersheds such as those at the Wye Research and Education Center (Staver and Brinsfield, 2001) so that results can be compared and correlated for several storms with regard to P concentrations and volumes of runoff.

Figure 8. Example of 0.31 m² erosion weir installed in drilled rye cover crop plot in October. Site must have at least 5% slope for this apparatus to work effectively. The collection 8-liter (2 gal) jug is sized to collect all the runoff anticipated from a 5 cm (2 inch) storm.

The mini erosion weirs are 75 cm long and 40 cm wide. They are installed facing downslope, 5 cm below the ground surface with 10 cm above the ground. The weir collects runoff from natural rain events on a 0.31 m^2 area. A 0.5 inch I.D. tube carries the runoff and sediment to a 2 gallon buried jug located 1 m downslope from the weir (Figure 7). In early October 2019 we installed 16 of these weirs, one in each of four replicated plots of four cover crop treatments. Three replications were in one field (25E) with a relatively fine textured sandy loam over clay loam soil, while the fourth replication was in a second field (39A) with a much coarser loamy sand over sandy loam soil. The cover crop seed was drilled on 26 August just after the last rain for 7 weeks. Fortunately, the seeds germinated quickly in warm soil and the rooted seedlings survived the severe drought that ensued for all of September and half of October. The appearance of the cover crops and the runoff weirs in mid-October 2019 is illustrated in Figure 8. The weirs were meant to be left in the ground until spring planting in late April or early May, but the Corona Virus lockdown forced us to stop our sampling campaign and remove the weirs in mid-March. We were able to sample a total of nine runoff-producing rain events between 18 October 2019 and March 2020.

Figure 9. The four cover crop treatments as they appeared on 18 October when the first runoff samples of the season were collected. Evidence of runoff and erosion can be seen in the control plot to the right of the metal weir.

The Cornell Sprinkler Infiltrometer rainfall simulator can be moved from plot to plot and is not permanently installed in the field. It does not depend on natural rainfall events but provides its own simulated rain at a set intensity using deionized water. This apparatus was developed at Cornell University and involves about 100 small tubes that provide droplets that produce "rain" at a controlled rate. All of the rain is confined by a metal ring inserted 7.5 cm into the soil so that the water either infiltrates the soil vertically or runoffs off the surface downslope. The runoff has to leave the circular soil area through a tube that leads to a collection bottle buried at a lower elevation. Using a constant rainfall rate, the simulator can determine hydrologic parameters such as time after rain initiation when runoff begins and soil infiltration capacity. It also allows for collection of the runoff water to measure its volume and analyze its contents (Figure 10).

The PI's lab purchased two of these Cornell Sprinkler Infiltrometers in 2019 with MSB funds from this project. They can be most efficiently used two at a time in tandem. One operator can set up one Infiltrometer while another operator is making measurements and collecting samples with the second Infiltrometer. The Infiltrometer can be used where a large number of treatments are involved or where the travel time to sample after each natural rain event would be prohibitive.

As described in the manual for the Cornell Sprinkle Infiltrometer (Van Es and Schindelbeck, 2005), it can be used to measure a number of important soil hydrologic properties including time to initiation of runoff, infiltration rate, runoff rate, saturated hydraulic conductivity and soil sorptivity. This is accomplished by calibrating the rainfall rate to a known value that is high enough to produce runoff from even sandy soil in a relatively short period of time approximately 30 minutes). The volume is runoff is then monitored over time to enable calculation of these soil properties as described below. We recorded the times (elapsed after initiation of rainfall) that the first drop of runoff occurred, and then the time elapsed when we collected each ~900 mL sample. We collected samples until the time elapsed between samples was essentially constant (generally five or six 900 mL samples over a period of 30 to 45 minutes of steady simulated rainfall).

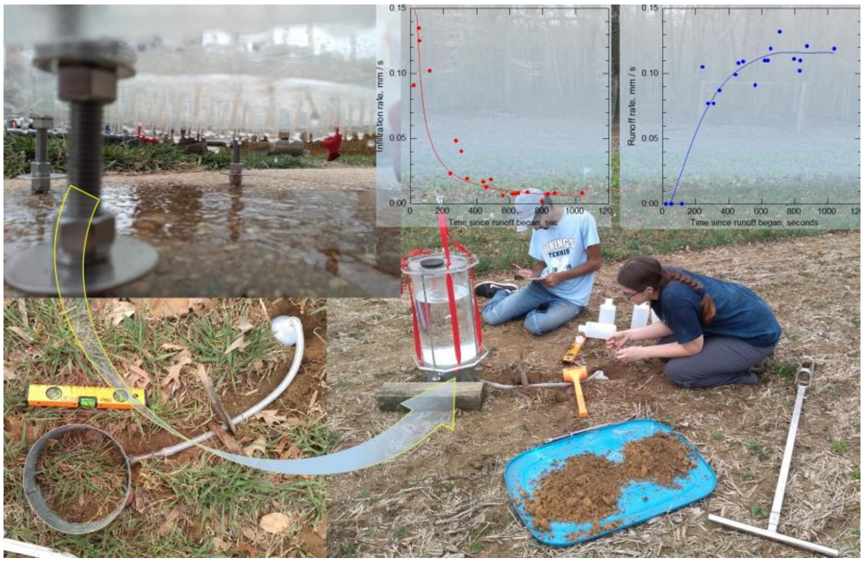

Figure 10. How the Cornell Sprinkler Infiltrometer was used in this runoff study. Upper left shows the drippers emitting simulated rainfall at a rate of ~ 30 cm/hr. Lower left show the metal ring, runoff delivery tube and runoff collection bottle installed in a drilled rye cover crop plot. Lower right shows the collection of samples and time intervals during sprinkler operation in the field. Upper right provides examples of the type of data collected showing infiltration rate (left) and runoff rate (right) over time.

Runoff rates (RO_t in cm/min) are determined as indicated in Equation 1.

EQ1 : RO_t (cm/min) = V_t cm^3 / (457.30 cm^2 * t min)

where 457.30 cm^2 is the area of the metal ring, and t is the time interval (minutes) it took for volume V_t of runoff water (cm^3) to be collected.

Infiltration rates at times t (I_t) are determined by the difference between the rainfall rate (cm/min) and runoff rate at time t as in equation 2:

EQ 2: $I_t = R - RO_t$

Estimation of Sorptivity

Time-to-runoff (TRO) is an important soil hydrological parameter that is dependent on the rainfall rate (r) as well as the initial soil water conditions. Runoff will occur earlier if r is higher and the soil is wetter. Sorptivity (S) is a soil hydraulic property that accounts for rainfall rates and assesses the speed infiltration early in a rainfall event. It includes effect of surface roughness that can cause micro-ponding of water. Sorptivity is estimated by equation 3 (Kutílek, 1980):

EQ 3:   S = (2TRO)0.5 * r

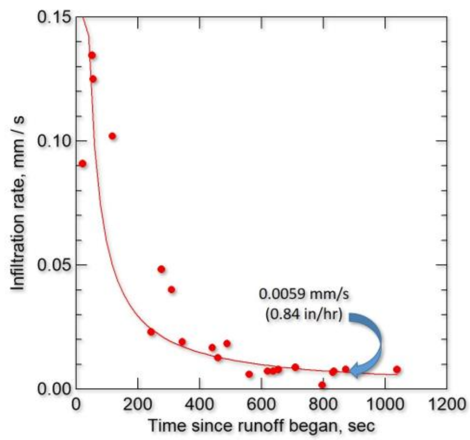

Figure 11. Saturated infiltration rate as estimated from Cornell Infiltrometer data on four cover crop plots.

The steady-state infiltration capacity of the soil thoroughly wetted soil, the Field-Saturated Infiltrability (ifs), can be estimated from data at the end of a measurement period when the runoff rate has become constant. Since the Infiltrometer utilizes a single ring (as opposed to a double ring infiltrometer), the measured infiltration rate is adjusted for the fact that some water may flow horizontally below the depth of the ring insertion. This tendency for horizontal rather than purely vertical flow is greater in finer textured soils and when the ring is inserted to a shallower depth. Using numerical modeling Reynolds and Elrick (Reynolds and Elrick, 1990) suggested adjustment factors of 0.95 for a ring inserted 7.5 cm into a sand soil and 0.80 for loam soils (Van Es and Schindelbeck, 2005). For example, for a ring insertion depth of 7.5 cm on a loamy sand soil, the field-saturated infiltration rate is estimated in EQ 4:

EQ 4: $ifs = It * 0.95$

Lab analysis of runoff samples.

Runoff water samples from both types of apparatus are meant analyzed for the following parameters.

1. Volume of runoff, expressed as millimeters or inches as well as percent of rainfall.
2. Amount of sediment in runoff, expressed as kg per hectare or pounds per acre.
3. Concentration of total phosphorus as milligrams per liter
4. Concentration of dissolved reactive phosphorus as milligrams per liter
5. Concentration of dissolved organic phosphorus is milligrams per liter

Prior to determination of dissolved phosphorus the runoff water samples were vacuum filtered through a 0.45 micron polycarbonate membrane. Organic phosphorus is determined as the difference in dissolved reactive phosphorus before and after persulfate digestion (Johnes and Heathwaite, 1992). All phosphorus analyses are run on a Lachat flow auto analyzer using an ortho-phosphate manifold and a modification of the ascorbic acid method (Watanabe and Olsen, 1965). Loading of the various forms of phosphorus are calculated as P concentration x runoff volume can be expressed as mg/m2, kg/ha or pounds per acre.

Because sampling continued until near the end of the project period, lab analysis of the samples collected is only partially complete at this time. Runoff volume has been measured on all samples, but sediment and various forms of P remain to be analyzed on some samples after Covid19 restrictions are eased. This included digestion of all samples to determine total dissolved and sediment-borne P.

Results can be reported for each natural rainfall event great enough to generate runoff from the mini erosion weirs. In addition, the loss of water, sediment and phosphorus from individual rain events can be summed up to calculate the total losses for the season.

PRELIMINARY RESULTS.

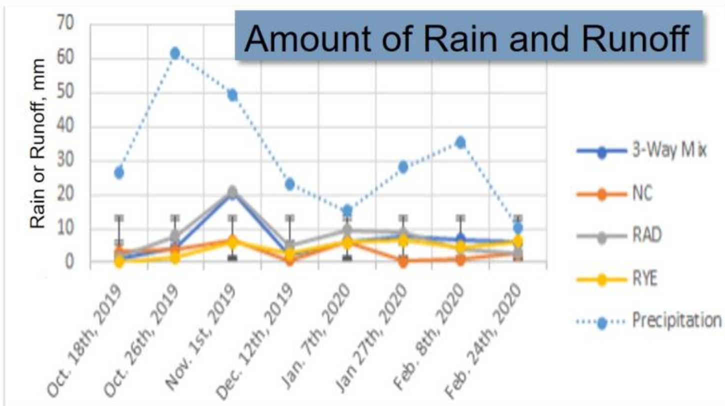

Figure 12. The amount of runoff produced during eight rain events sampled between 18 October 2019 and 24Feb. 2020.

Figure 12 shows the amount of rainfall for the eight events sampled between October 18th, 2019 and February 24th 2020. The latter was the last event sampled before the COVID-19 restrictions came into play and prevented sampling of later events. In early March, the runoff weirs and other equipment items were all removed from the fields so they would not interfere with cover crop termination and crop planting while our University student labor team was in lockdown. As expected for runoff, the data are quite variable. However, even after transforming the data, analysis of variance showed that none of the cover crop treatments had a significant impact on the amount of water lost as runoff.

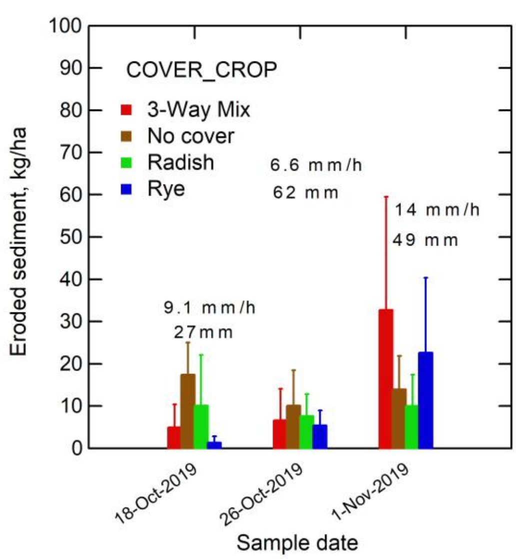

Figure 13. Sediment loss from the sandy no-till soil during the first three storms sampled were very low and not significantly affected by any cover crop treatment. The total amount and maximum hourly intensity for each event are shown above the bars.

Figure 13 shows the amount of eroded settlement for each of the first three runoff producing rain events in falls 2019. The figure also shows the rainfall amounts for each event and the maximum one-hour intensity. Because of Highly protective nature of a long term no tell residue covered soil as well as the highly variable nature runoff and erosion data no significant effect of cover drop could be discerned. It appears that the amount of sediment produced was more closely related to the one-hour intensity then the total amount of rain falling in the three events. All cover crops were no till drilled so there was no comparison this year with a broadcast seating and any effect of the disturbance of the soil by the drill could not be discerned. Samples from the other five runoff generating rain events still await analysis for sediment and P associated with the sediment. In any event, the amounts of sediment generated by these storms was very low, even for the plots with no cover crop. Research in the literature usually reports far greater sediment loses from comparable storms where soil tillage is routinely used. These low sediment loss rates are not unexpected from long term no-till soil with nearly complete residue cover, as is typical for many Maryland farms.

The concentration of phosphate (PO_4) phosphorus dissolved in the runoff from the first five runoff producing rain events is shown in the upper graph in Figure 14a. As a reference, US Geologic Survey guidance for eutrophication in flowing stream water is about 0.1 mg P/L. The dissolved PO_4-P was generally below 0.2 mg/L for all plots, but the concentrations in the runoff from the 18 October 2019 samples were considerably higher than for the later dates. We speculate that first rain after 7 weeks of hot dry weather resulted in a flush of microbial activity releasing P from soil organic matter and crop residues on the soil surface, leading to the higher levels of P in the first runoff event sampled. Despite the large variability in P concentrations on that date, the runoff from the rye cover crop plots had significantly lower P concentration than that from the 3-way mix cover crop plots. This difference in concentration was at least partially due to the fact that the highest concentrations occurred were associated with the lowest runoff volumes. For this reason, the *amount* of PO_4-P lost in the runoff sampled 18 October did *not* differ among cover crop treatments. In fact, Figure 15 shows there was no significant cover crop effect on the amount of P lost in runoff (g P/ha) on any of the five dates analyzed at the time of this report.

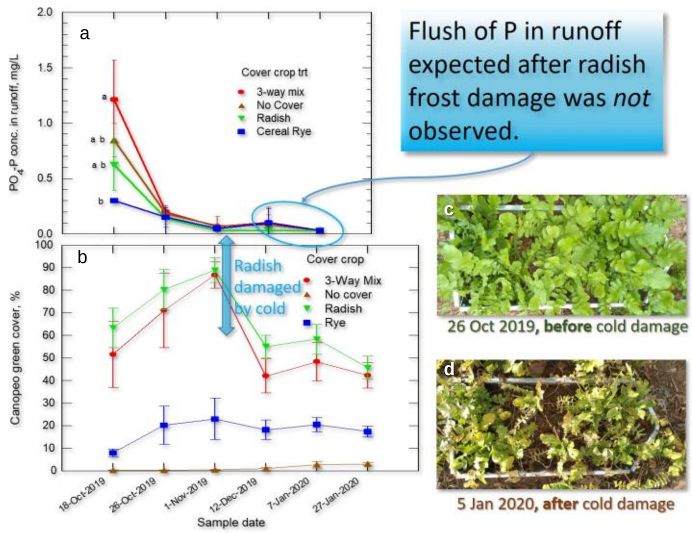

Figure 14. Phosphate-P concentration in runoff (a) and living leaf groundcover percentage (b) for the four cover crop treatments and the appearance of the radish plants before (c) and after (d) cold injury which occurred in November 2019.

Figure 14(b-d) show that the radish plants in both the 3-way mix and in the sole species radish cover crop were severely injured (but not killed) in November (on November 9 and 13 night temperatures went down to -7 ^{o}C = 20^{o}F). Most of the radish foliage was killed and many of the fleshy roots were also injured as shown in the images of Figure 14c-d. This damage was quantified by the CANOPEO estimates of green groundcover percentage which dropped dramatically for the radish and 3-way mix (but not for the Rye) between 1 November 12 December 2019.

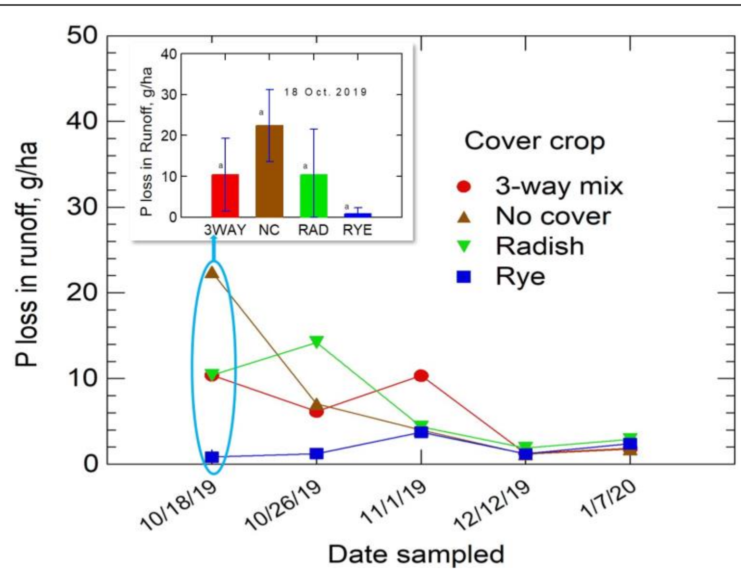

Figure 15. The amount of PO_4-P lost in runoff produced during five rain events sampled between 18 October 2019 and 01 January 2020. There was no effect of cover crop on any date sampled. Inset shows data variance and lack of significant any differences in the 18 October samples.

One of the main hypotheses motivating this research was the expectation that cold injury or death of frost susceptible cover crops such as radish would release large amounts of phosphorus from injured cells and that this soluble P would result in a large spike in P concentration in runoff water from the rain events following such winter-injury of the radish plants. However, it is clear from the data in Figure 14a that no such spike occurred in the concentrations of P in runoff after the radishes were injured. To the contrary, the concentration of P in runoff from all treatments remained very low.

The results of this year's runoff research are perhaps best summarized by the data presented in Figure 16 which show the cumulative amounts of runoff water, sediment loss and phosphate-P loss in runoff for all the samples analyzed to date. Between 18 October 2019 and 24 February 2020, an average of 12.8% to 30.2% of the rainfall was lost as runoff during eight runoff-generating events totaling 250 mm of precipitation. This is not counting several rain events that were too light to cause any runoff from any of the plots. Cumulative sediment losses from the first three events were very modest, ranging from 32 to 53 kg sediment per hectare. To put these values in perspective, since they were from only three storms over two months, we could multiply these losses by 6 times to estimate annual rates of sediment loss between 192 and 315 kg/ha. These figures can be compared to the 2 to 4,000 kg/ha annual loss that is considered "tolerable" (T-value) for similar soils by the USDA/NRCS. The amount of dissolved phosphate-P lost in the runoff from the first five events over 4.5 months ranged from 8 to 36 grams of P per hectare (0.1 to 0.5 ounces/acre). If we again assumed a similar rate of P loss through the year, the annual loss of dissolved phosphate-P would range from 21 to 107 g P/ha. While other forms of P (organic and sediment bound) in the runoff remain to be analyzed, these very low levels of dissolved phosphate-P loss in runoff from moderately high P fertility soils (Mehlich3 P ~ 150) under no-till management with crop residue cover should be encouraging.

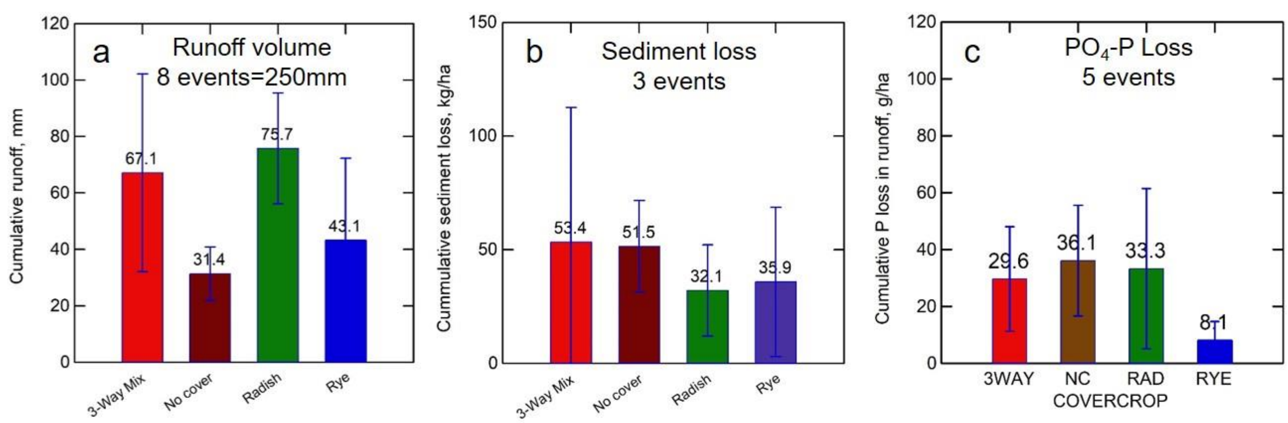

Figure 16. Cumulative runoff amount (a), sediment loss (b), and dissolved PO_4-P loss (c) during the 2019-2020 study period. The number of runoff -generating rain events included for each parameter differs because the Covid19 restrictions imposed in March 2020 prevented completion of sediment and P analyses for some samples dates.

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