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A Protocol for Conducting Rainfall Simulation to Study Soil Runoff

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Abstract:	Rainfall is a driving force for the transport of environmental contaminants from agricultural soils to surficial water bodies via surface runoff. The objective of this study was to characterize the effects of antecedent soil moisture content on the fate and transport of surface applied commercial urea, a common form of nitrogen (N) fertilizer, following a rainfall event that occurs within 24 hours after fertilizer application. Although urea is assumed to be readily hydrolyzed to ammonium and therefore not often available for transport, recent studies suggest that urea can be transported from agricultural soils to coastal waters where it is implicated in harmful algal blooms. A rainfall simulator was used to apply a consistent rate of uniform rainfall across packed soil boxes that had been pre-wetted to different soil moisture contents. By controlling rainfall and soil physical characteristics, the effects of antecedent soil moisture on urea loss were isolated. Wetter soils exhibited shorter time from rainfall initiation to runoff initiation, greater total volume of runoff, higher urea concentrations in runoff, and greater mass loadings of urea in runoff. These results also demonstrate the importance of controlling for antecedent soil moisture content in studies designed to isolate other variables, such as soil physical or chemical characteristics, slope, soil cover, management, or rainfall characteristics. Because rainfall simulators are designed to deliver raindrops of similar size and velocity as natural rainfall, studies conducted under a standardized protocol can yield valuable data that, in turn, can be used to develop models for predicting the fate and transport of pollutants in runoff.

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United States Department of Agriculture

Research, Education and Economics
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JoVE Editor
17 Sellers Street
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Dear Sir or Madame:

Please accept the enclosed materials for publication in JoVE, the Journal of Visualized Experiments. If accepted for publication, my co-authors and I are prepared to cover the publication costs associated with having JoVE produce an open source video showing the operation and calibration of a rainfall simulator. This rainfall simulator is widely used by researchers in North America for studying environmental contaminant losses from agricultural soils. There is a need for standardizing the protocol for using this simulator so that results across separate studies conducted by different researchers can be used in support of modeling efforts.

All of the authors contributed to conducting the rainfall experiment assessing the effects of antecedent moisture on runoff which serves as the example for data collection and analysis. The first and second authors and myself contributed to writing the manuscript. The remaining authors provided reviews and suggested edits to improve the manuscript. As a result, I think you will find this to be a well polished effort that conforms to journal standards and format. We wish to thank Joni Williams, Associate Editor for JoVE, for making us aware of this journal and providing materials that guided our effort to develop this manuscript.

If accepted for publication, we propose the video be shot at the USDA-ARS location on the Penn State campus in State College, PA, a three hour drive from Pittsburg. Our collaborators from the University of Maryland Eastern Shore, a historically black 1890's university, will join us for the filming.

Attached is a list of peer reviewer's names, institutional affiliation and email addresses.

Sincerely,

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Keywords: Rainfall simulator; artificial rainfall; runoff; packed soil boxes; nonpoint source; urea

Short Abstract:
A rainfall simulator was used to apply a consistent rate of uniform rainfall to packed soil boxes in a study of the fate and transport of urea, a nonpoint source environmental contaminant. Under uniform soil and rainfall conditions, antecedent soil moisture content exerted strong control over urea loss in surface runoff.

Long Abstract:
Rainfall is a driving force for the transport of environmental contaminants from agricultural soils to surficial water bodies via surface runoff. The objective of this study was to characterize the effects of antecedent soil moisture content on the fate and transport of surface applied commercial urea, a common form of nitrogen (N) fertilizer, following a rainfall event that occurs within 24 hours after fertilizer application. Although urea is assumed to be readily hydrolyzed to ammonium and therefore not often available for transport, recent studies suggest that urea can be transported from agricultural soils to coastal waters where it is implicated in harmful algal blooms. A rainfall simulator was used to apply a consistent rate of uniform rainfall across packed soil boxes that had been pre-wetted to different soil moisture contents. By controlling rainfall and soil physical characteristics, the effects of antecedent soil moisture on urea loss were isolated. Wetter soils exhibited shorter time from rainfall initiation to runoff initiation, greater total volume of runoff, higher urea concentrations in runoff, and greater mass loadings of urea in runoff. These results also demonstrate the importance of controlling for antecedent soil moisture content in studies designed to isolate other variables, such as soil physical or chemical characteristics, slope, soil cover, management, or rainfall characteristics. Because rainfall simulators are designed to deliver raindrops of similar size and velocity as natural rainfall, studies conducted under a standardized protocol can yield valuable data that, in turn, can be used to develop models for predicting the fate and transport of pollutants in runoff.

Introduction:
The environmental impacts of agriculture are a global and rapidly increasing concern, especially in light of the uncertainties of global change. Rainfall is a driving force for the transport of environmental contaminants from agricultural soils to surficial water bodies via surface runoff. A large body of research is focused on better understanding the interactions between rainfall and soil conditions as they determine nonpoint sources of sediment, nutrient and pesticide losses from agricultural soils. The objective of this study was to characterize the effects of antecedent soil moisture content on the fate and transport of surface applied commercial urea, a common form of nitrogen (N) fertilizer, following a rainfall event that occurs within 24 hours after fertilizer application.

There are few studies of the fate and transport of urea in soils, because urea is rapidly hydrolyzed to ammonium following fertilizer application and therefore not often available for transport. However, recent watershed studies suggest that urea can be transported from agricultural soils to coastal waters and cause shifts toward populations of organisms that produce harmful toxins [1, 2]. Both laboratory and field experiments have shown that when the domoic acid-producing diatom *Pseudo-nitzschia australis* (*P. australi*s) was grown in urea enriched seawater, the amount of domoic acid produced was greater than when grown on nitrate- or ammonium-enriched seawater [3]. This study used simulated rainfall to investigate the processes that control the potential for urea-N losses in runoff following commercial fertilizer application.

Due to the variability of natural rainfall, rainfall simulators have been used to apply uniform rainfall rates over land surfaces or packed soil boxes to evaluate runoff under controlled conditions. Rainfall simulators were initially used to study soil erosion [4]. However, over the years they have been used to measure other constituents in surface runoff and leachate from soils [5, 6, 7]. Field studies using natural rainfall have also been conducted to assess losses of soil constituents in runoff. Trends between natural rainfall and rainfall simulation data follow a similar pattern, pointing to a consistency in processes. Therefore rainfall simulation can be used in studies to predict the likely occurrence of what happens under natural rainfall [8].

A variety of rainfall simulators have been developed, and typically they use nozzle sprayers to apply water at desired rates and durations. In terms of size, rainfall simulators range from a simple, small, portable infiltrometer with a 6-inch-diameter rainfall area [9] to the complex Kentucky rainfall simulator, which covers a plot 14.75 ft by 72 ft (4.5 m by 22 m) [10]. One shortcoming in the body of research that employed rainfall simulation is that there is no single standardized design or protocol for conducting rainfall simulations [11]. In fact, at the 2011 "International Rainfall Simulator Workshop" at Trier University, Germany, a collaborative community of scientists from 11 participating countries concluded that a standardization of rainfall simulation and simulators is needed in order to ensure the comparability of results and to promote further technical developments to overcome physical limitations and constraints [12]. This study seeks to partially address that need by presenting a detailed description of a standardized protocol for conducting rainfall simulations using a simulator that is already widely adopted for use in North America.

This experiment is part of a larger study designed to assess the source of urea in estuarine waters of the Chesapeake Bay where toxic algal blooms are known to occur annually. The specific objective of the experiment was to determine the effect of antecedent soil moisture content on urea losses in runoff. Duplicate uniformly packed soil boxes were pre-wetted to one of six different moisture contents representing 50, 60, 70, 80, 90, and 100 % of field capacity. Urea was surface applied in prill form at a rate of 150 kg N ha^{-1}. Within 24 hours the boxes were subjected to uniform rainfall of 40 minute duration at a rate of 3.17 cm hr^{-1}, equivalent to a natural precipitation event that commonly occurs on an annual basis on the Eastern Shore of the Chesapeake Bay in Maryland. Runoff samples were collected at 2 min intervals, immediately filtered using a glass filter (0.45 µm), and stored at 4^{o} C until they were analyzed within 24 hr of collection. Urea-N concentrations were determined by flow injection analysis colorimetry [13]. Data were analyzed using SAS v.9.1 [14], and statistical results were considered significant at $P \leq 0.05$.

The portable rainfall simulator that was utilized in this study meets the design specifications [15] and protocol that was developed by the National Phosphorus Project [16]. In the U.S. and Canada, this simulator design and protocol has been widely adopted as the standard method for use in determining both dissolved and particulate-bound phosphorus loss in runoff. Although runoff samples were analyzed for urea rather than phosphorus, the method for applying uniform and consistent rainfall to packed soil boxes is the same as that which is briefly described in the National Phosphorus Project rainfall simulation protocol.

Protocol Text:

1. Soil collection and preparation

1.1) Collect the soil from the surface horizon of the soil profile to accurately represent physical and chemical conditions of the soil surface. Note: If possible soil should be collected from the top 5 cm of the surface. The area for soil collection should be small enough to limit variation in soil physical and chemical properties.

1.2) Sieve the soil through a coarse (20 mm) screen to remove rocks. Note: Sieving is easier if the soil is somewhat moist.

1.3) Spread the sieved soil out on a heavy tarpaulin in a thin layer to facilitate drying, preferably in a green house or warm indoor environment.

1.4) Mix the soil with a shovel, rake or by pulling the edges of the tarp from one side to the other as if folding a giant calzone. Note: Be careful not to rip or tear the tarp with the edge of a shovel or rake. Repeat this process several times until the soil is thoroughly mixed.

1.5) Take 10 samples from different places in the pile of thoroughly mixed soil and conduct a Mehlich-3 phosphorus test [17] to test for homogeneity. Note: Homogeneity is achieved when the results of the 10 samples have a coefficient of variation (CV) of < 0.05. Where: CV = standard deviation/mean.

1.6) If the CV of the Mehlich-3 phosphorus test is > 0.05, continue mixing the soil and repeat the homogeneity test.

2. Packing soil boxes

2.1) Note: Soil boxes should be of uniform volume with identical dimensions of length, width and depth (100 cm x 20 cm x 7.5 cm) with nine 5-mm drain holes in the bottom. Boxes should have a 5 cm lip and a collection gutter on one end (**Figure 1**).

2.2) Line the bottom of the boxes with 4 ply cheese cloth to keep soil from washing out of the holes in the box while allowing water to flow through when the soil is saturated.

2.3) Pack the first soil box by scooping enough dried, sieved, and homogenized soil into the box to fill it about half deep when smoothed out (about 3.5 cm). Spread the soil evenly and pack it

with a flat brick. Note: Soil should be sufficiently dry so it does not compact under the pressure of the brick.

2.4) Add another 2 cm of soil and level it out with a leveling gage to a packed depth of 5 cm, the height of the lip of the box that spills into the gutter. (**Figure 2**).

2.5) Weigh the amount of soil that was added to the first packed box, and add the same weight of soil to all remaining boxes. Pack each box to achieve a soil depth of 5 cm and uniform bulk density.

3. Mounting soil boxes in the rainfall simulator

3.1) Position a frame constructed out of 2" x 6" pressure treated lumber in the center of the rainfall simulator upon which the soil boxes will be placed. Note: The frame should have a cross member in the middle to provide rigidity. Placing soil boxes on a bottomless frame minimizes splash that would otherwise occur from a solid platform immediately below the soil boxes and allows free drainage from the holes in the bottom of the boxes.

3.2) Position the frame on cement blocks at a height that allows placement of collection bottles and funnels below the spouts on the collection gutters at the front of soil boxes mounted on the platform.

3.3) Further elevate the back of the platform, using bricks, lumber and shims, such that the back of a soil box placed on the platform is 3 cm higher than the front of the box, resulting in a 3 % slope. Measure the slope by placing a board (> 100 cm length) on the back of a soil box mounted on the platform. Using a carpenter's level, hold the board level and raise the back of the platform such that the front of the box is 3 cm below the level board (**Figure 3**). Note: Be sure the front and back of the platform is level from side to side.

3.4) Locate the point directly below the overhead nozzle and avoid placing a box in that position to avoid large drops from the nozzle at the beginning or end of a rainfall event from falling on a soil box, then place five or six boxes evenly spaced on the platform. Mark the position of the boxes and always place boxes in these same positions.

4. Selecting the source of irrigation water

4.1) Select an irrigation water source that is relatively free of all elements and compounds, particularly those of interest to the study. Analyze the water source in advance of the study to determine water purity. Note: If necessary, exchange resins should be used to achieve desired water purity.

4.2) Provide a main water source to the rainfall simulator that exceeds a pressure of 8 psi and a flow rate of 5 gpm. Note: Normal municipal sources exceed these minimum requirements. If using water tanks and pumps, be sure the pumps are capable of delivering a water supply that exceeds the minimum pressure and flow rate.

5. Selecting the nozzle size to use

5.1) Select one of four standard nozzle sizes that are used for rainfall simulations. Note: Each nozzle has an optimal performance pressure and flow to achieve proper droplet size and intensity (**Table 1**). Selection of nozzle size for use in a particular study is determined in relation to the intensity (cm hr^{-1}) of the natural rainfall event to be represented.

6. Rainfall simulator operation

6.1) Position the (1) single lever ball valve (**Figure 4**) to the closed position, lever at 90 degree angle across pipe, and turn on the main water source (municipal or pump).

6.2) Turn the square set screw on the top of the (3) pressure regulator valve (**Figure 4**) counter clockwise to reduce the pressure and open the next-in-line (4) in-line flow control valve completely.

6.3) Open the (1) single lever ball valve (**Figure 4**) completely and adjust the (3) pressure regulator valve by turning the set screw clockwise to achieve approximately 8 psi in the (6) pressure gauge located near the top of the rainfall simulator. Note: Once the (3) pressure regulator valve has been set to slightly exceed the desired nozzle pressure, it should not have to be adjusted during the operation of the rainfall simulator unless the main water source pressure changes.

6.4) Partially close the (4) in-line flow control valve (**Figure 4**) until the (5) flow meter reads the approximate flow rate in gallons per minute for the nozzle in use and the (6) pressure gauge reads the approximate psi for the nozzle in use (**Table 1**).

6.5) Close the (1) single lever ball valve (**Figure 4**) to stop the flow without changing the flow rate and pressure settings.

7. Nozzle calibration and rainfall uniformity

7.1) Cover the holes in the bottoms of 5 or 6 empty soil boxes with duct tape to prevent water from leaking out of the boxes and place them in the marked positions on the wooden frame (see step 3.4).

7.2) Position and hold a 10 foot length of 2 inch pvc pipe with a 45 degree elbow attached to the end over the nozzle and open the (1) single lever ball valve.

7.3) Collect the discharge from the pvc pipe in a large graduated cylinder for 10 seconds.

7.4) Make minor adjustments to the (4) in-line flow control valve and repeat the 10 second collections until the 10 second flow volume matches the corresponding value for the nozzle in use (**Table 1**). Once the correct flow rate is achieved, use the value on the flow meter as a means of monitoring variation in flow due to possible pressure fluctuations. Note: For properly

calibrating the nozzle, the 10 second flow volume is a more accurate measure than the reading on the flow meter.

7.5) Remove the 10 foot length of pvc pipe to allow rainfall to wet the box area and note the time of rainfall initiation.

7.6) After exactly 10 minutes abruptly stop the rainfall by positioning the 10 foot pvc pipe over the nozzle to divert flow and close the (1) single lever ball valve.

7.7) Measure the volume of water (mL) collected in each box by pouring it into a graduated cylinder, and calculate rainfall depth by dividing volume by the area of the bottom of the box (2000 cm^2).

7.8) Calculate the coefficient of variation for rainfall depth. Note: Rainfall uniformity is achieved when rainfall depth in the 5 or 6 boxes has a coefficient of variation < 0.05. Where: CV = standard deviation/mean.

7.9) If the CV is not less than 0.05, turn the nozzle ¼ turn tighter and repeat the calibration process. Note: The nozzle might need to be turned several times to achieve a CV of less than 0.05.

7.10) Once a CV of less than 0.05 is achieved, repeat the calibration several times to ensure that rainfall intensity across runs is consistent.

8. Conducting a rainfall simulation

8.1) Following calibration, place packed soil boxes in the marked positions on the wooden frame (see step 3.4).

8.2) Position runoff collection bottles and funnels below the drain spouts and prevent rainfall from directly falling into the gutter by using a paper clip to attach a shield over the gutter (**Figure 5**).

8.3) Repeat steps 7.2 through 7.5 to recalibrate nozzle flow rate immediately prior to a rainfall simulation event and initiate rainfall.

8.4) Record the time of runoff initiation for each box when water draining from the drain spout turns from a slow drip to a continuous stream.

8.5) Collect runoff samples at prescribed time intervals during the event by switching collection bottles or at the end of an event of predetermined duration.

8.6) To terminate a rainfall event, stop the rainfall by positioning the 10 foot pvc pipe over the nozzle to abruptly divert flow and close the (1) single lever ball valve.

8.7) Collect the runoff samples and record volume using a graduated cylinder or by mass assuming that water weighs one gram per cubic centimeter.

8.8) Mix the samples thoroughly so that all sediment is in suspension and then take a subsample for laboratory analysis.

Representative Results:
One reason for conducting the current experiment was to explore factors that may have contributed to poor results from a previous experiment where urea loss in runoff was being compared across several forms of fertilizers and manures that contained urea. All treatments were applied to soils that had been saturated and allowed to drain to field capacity. Results for five replicates of the urea prill treatment ranged from concentrations of 1 to 12 mg L^{-1} urea-N in runoff. This order of magnitude variation among replicates was unacceptable under controlled conditions and confounded the results of the experiment. A strong positive relationship between total volume of runoff and urea-N concentration in runoff suggested that physical conditions, such as packing or variable antecedent moisture conditions due to different draining and drying conditions, were causative factors.

In order to investigate the cause for such extreme variation in urea concentrations in runoff, all boxes in the current experiment were carefully packed with equal weights of uniformly mixed silt loam soil as depicted in **Figures 1 and 2** to minimize variation in physical conditions. To achieve 50, 60, 70, 80, 90, and 100 % of approximate field capacity as determined by wetting, then oven drying a small quantity of sieved soil, the weight of water required to wet the soil to corresponding antecedent soil moistures of 14, 17, 19, 22, 25 and 27 % was calculated, added to the boxes, and allowed to equilibrate overnight. The rainfall simulation followed the exact protocol described above and depicted in **Figures 3 – 5**. The 17 wsq Full Jet 3/8 HH nozzle (**Table 1**) was used to deliver a rainfall intensity of 3.2 cm hr^{-1} over a 40 minute period which is equivalent to a natural precipitation event that commonly occurs on an annual basis on the Eastern Shore of the Chesapeake Bay in Maryland.

The resulting total runoff volumes, loads, and flow weighted concentrations are summarized in **Table 2**. There was a significant positive relationship between total runoff volume and antecedent moisture condition (**Figure 6**). Wetter soils had less capacity to store water and lower infiltration rates resulting in greater runoff volumes. There was a significant negative relationship between time to runoff and antecedent moisture condition (**Figure 7**). Water infiltrated into drier soils for a longer period of time before they became wet near the surface, causing runoff to occur. Not surprisingly, there was a positive relationship between total load urea-N in runoff and total runoff volume (**Figure 8**). It is well known in hydrologic studies that flow volume is usually a strong predictor of total load. How concentration will behave in response to a runoff event is less predictable. Flow weighted concentration was calculated by summing the loads for each 2 minute runoff collection and dividing by total runoff volume. It is equivalent to the concentration in a single collection of runoff at the end of the 40 minute rainfall period. In this study, there was a significant positive relationship between flow weighted concentration in runoff and antecedent moisture condition (**Figure 9**). Given the positive linear relationships between runoff volume and antecedent soil moisture and flow weighted concentration and antecedent moisture condition, a significant positive relationship between total

load urea-N and antecedent moisture condition was expected. However, this significant relationship was best described by an exponential equation (**Figure 10**).

In order to visualize urea-N loss in runoff over time, individual 2 minute concentrations and cumulative loads in one replicate of a soil box representing each antecedent moisture condition was plotted over the 40 minute rainfall time interval (**Figure 11**). Although concentrations in runoff can vary somewhat erratically over time (e.g., in the case of the 90% moisture), concentrations generally start high and decrease over time. Cumulative loads over time are much smoother functions, and they illustrate the significant relationships previously discussed. Time to runoff is longer, urea-N concentrations in runoff are lower, and cumulative loads are less for drier soils. Although urea hydrolyzes rapidly in soils, when rainfall occurs within hours of surface application, much of the N is still present in urea form and is subject to loss in runoff. Urea is a neutral molecule and is not strongly sorbed to the surfaces of soil particles. As water infiltrates the drier soils during the early part of a rainfall event it carries dissolved urea down into the soil and away from the surficial runoff zone. When runoff does begin, there is less urea present and concentrations in runoff are lower. From a practical sense, urea would almost always be applied under drier conditions as farm equipment could not traverse soils that are at field capacity.

Figures and Tables:

Figure 1: Schematic of packed soil runoff box. A metal box (100 cm x 20 cm x 7.5 cm) with a 5 cm lip on the forward end is packed with soil to a depth of 5 cm. Runoff that spills over the 5 cm lip is collected in an attached gutter that is shielded against rainfall falling directly into the gutter. Nine 5 mm diameter holes allow water that infiltrates the soil to drain from the boxes and prevent ponding. A nipple attached near the forward edge of the bottom of the gutter allows runoff water to drain into funnels and collection bottles positioned below the nipple.

Figure 2: Box packing materials. Approximately 4 layers of cheesecloth in the bottom of the box prevent soil loss but allow water to drain freely. A leveling gage consisting of acrylic glass sandwiched between two wooden boards is as wide as the box (20 cm) and as deep (2.5 cm) as the difference between the sides of the box (7.5 cm) and the top of the gutter (5 cm). By resting the board on the lip of the box the acrylic glass is used to grade soil to the depth of the gutter.

Figure 3: Positioning the platform. Position the platform so that when the packed soil boxes are in position, they all have the same slope. For this study, the desired slope was 3 percent. While holding a board level, position the platform so that the down slope, gutter end of the box is 3 cm below the upslope end. The platform should be level in the cross slope direction.

Figure 4: Rainfall simulator controls beginning from the water source and progressing through the plumbing system to the nozzle. (1) Single lever ball valve: This is a quick shutoff valve. Lever in line with pipe is on; lever at 90 degree angle across pipe is off. Use this valve to turn flow on and off without disturbing valves that control pressure and flow rate. Open fully and close fully. Do not try to use this valve to control flow rate. (2) Sediment filter: Check filter periodically and replace element as needed to prevent clogging with sediment. (3) Pressure regulator valve: This valve controls the pressure in the line from this point forward. Too much

pressure may break pipes, hoses or connections. (4) In-line flow control valve (Gate valve): This valve is used to fine tune the flow to the nozzle in order to achieve the desired flow rate and nozzle pressure. (5) Flow meter: Measures approximate flow rate. (6) Pressure gauge: Measures approximate pressure at the nozzle.

Figure 5: Boxes positioned on the platform for rainfall simulation. Place 5 or 6 boxes in marked positions for each rainfall simulation event. Avoid positioning a box directly under the nozzle to prevent dripping directly onto a box surface.

Figure 6: Total runoff volume is positively correlated with antecedent soil moisture content ($R^2 = 0.64$).

Figure 7: Time to runoff is negatively correlated with antecedent soil moisture content ($R^2 = 0.48$). The surface of a wet soil saturates quickly. Rainfall that exceeds the hydraulic conductivity of the saturated soil generates runoff.

Figure 8: Total load urea-N is positively correlated with runoff volume ($R^2 = 0.81$). Differences in runoff volume overwhelm differences in concentration of urea-N in runoff.

Figure 9: Flow weighted concentration of urea-N is positively correlated with antecedent soil moisture content ($R^2 = 0.66$). Drier soils allow infiltration that leaches urea-N into the soil and away from the soil surface. When runoff does occur, less urea-N is available at the surface for movement in runoff.

Figure 10: Total load urea-N is positively correlated with antecedent soil moisture content ($R^2 = 0.74$). The positive relationships between total runoff volume and antecedent soil moisture content and between flow weighted concentration of urea-N and antecedent moisture content combine to result in an exponential relationship ($y = 0.2043\ ^{e0.0405x}$).

Figure 11: Urea-N concentration and cumulative load relationships over time for one replicate of each antecedent soil moisture content. Although urea-N concentration is not always a smooth function through time, the significant relationships previously discussed can be visualized.

Table 1: Nozzle size chart. Nozzle sizes that have been identified for use with this rainfall simulator and their associated rainfall intensity, pressure and flow parameters are presented. Selection of nozzle size depends on the desired rainfall intensity. Rainfall intensity and duration correspond to a precipitation event of a certain return period for a specified study location. Nozzle size 17 wsq was used for this study. Rainfall of 40 minute duration at an intensity of 3.2 cm hr^{-1} is equivalent to a natural precipitation event that commonly occurs on an annual basis on the Eastern Shore of the Chesapeake Bay in Maryland.

Table 2: Antecedent soil moisture content, total runoff volume, flow weighted urea-N concentration and total urea-N load after rainfall simulation. Duplicate numbers represent two replications for each moisture level

Discussion:

Runoff is mainly generated by two mechanisms, infiltration excess runoff and saturation excess runoff [18] and is influenced by soil properties, antecedent soil moisture, topography, and rainfall intensity. Rainfall simulation can be used to fix the rainfall intensity variable and study one or more of the remaining variables. Rainfall intensity and duration can also be controlled over a limited range for study by changing the nozzle size. The most critical steps for conducting rainfall simulation studies on packed soil boxes are: 1) ensuring uniform packing of soil boxes; 2) controlling antecedent soil moisture content; 3) calibrating flow rate for the selected nozzle so that drop size and velocity approximates natural rainfall; and 4) adjusting nozzle position to ensure uniform rainfall across all soil boxes.

At the end of the calibration process, once a CV of less than 0.05 is achieved for rainfall uniformity across all soil boxes, the 10 minute calibration should be repeated several times to ensure that rainfall intensity across runs is consistent. A CV can also be calculated for uniformity across runs. If the CV for uniformity across runs is less than that for uniformity of rainfall across all boxes, consider grouping replicate treatments within individual runs to minimize variation across treatments. Otherwise, to reduce the error associated with box position and across runs, randomize both treatments and replicates according to box position, taking steps to limit placing a treatment in a position more than once.

Using this rainfall simulator design and a standard protocol for properly calibrating the simulator will improve comparisons of results across studies conducted by different researchers. The data derived this way can be used to predict what happens under natural rainfall and better understand the processes and factors that control losses to the environment from nonpoint sources of contaminants. Such studies can yield valuable data for use in developing models for predicting the fate and transport of sediment and chemical pollutants in runoff under natural rainfall conditions.

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Disclosures: The authors declare that they have no competing financial interests.

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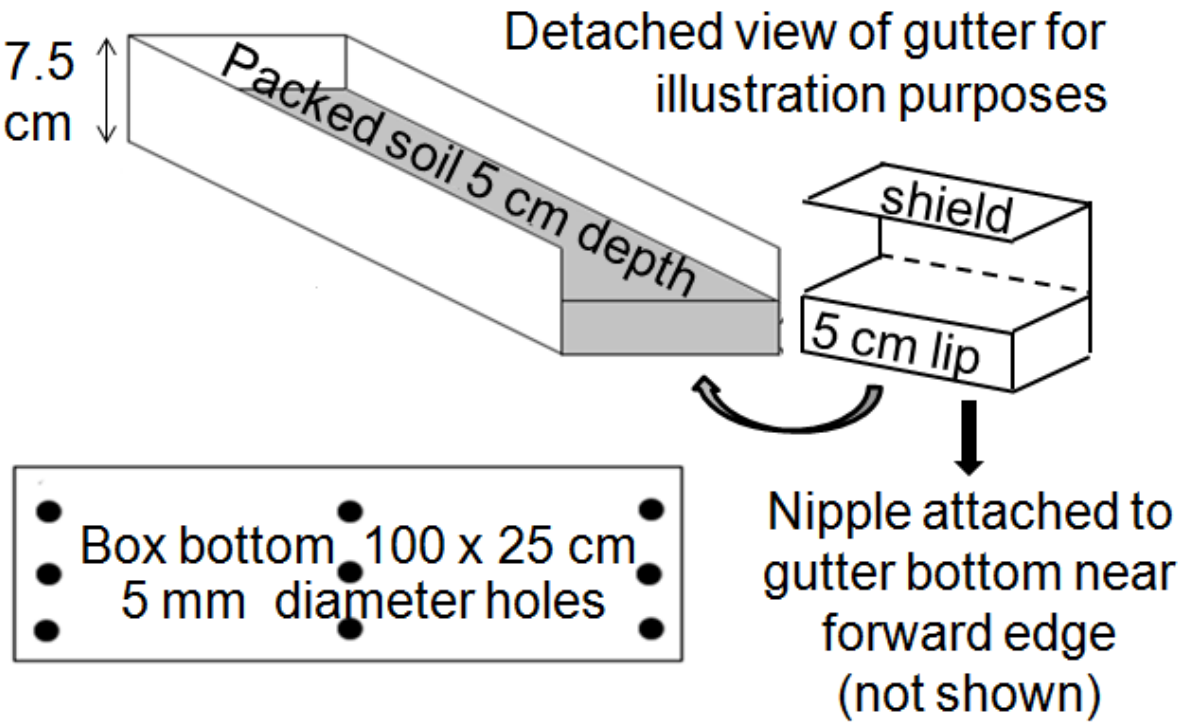

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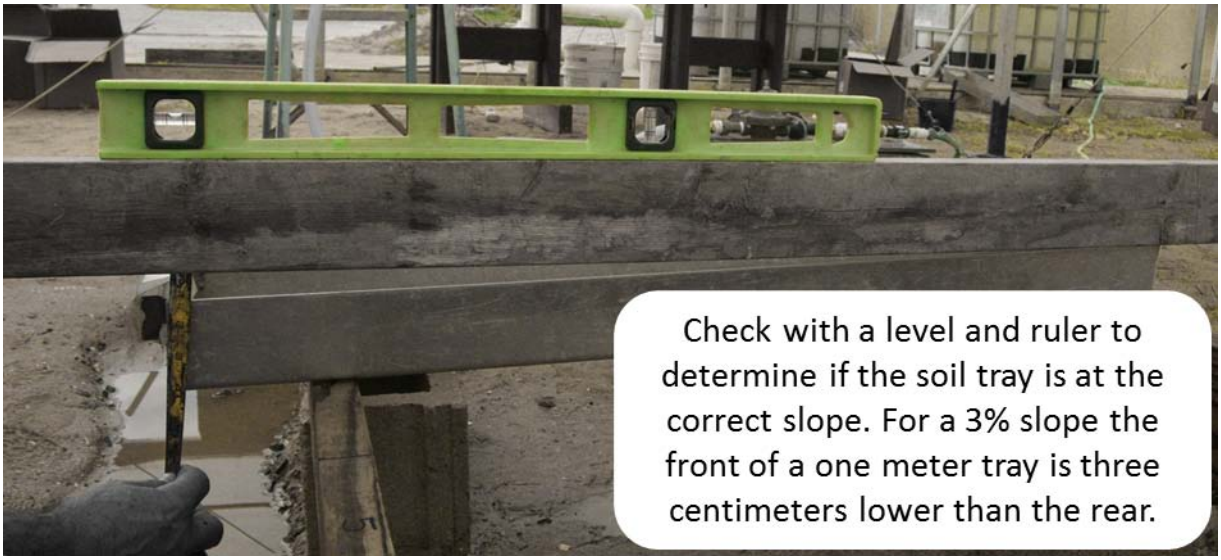

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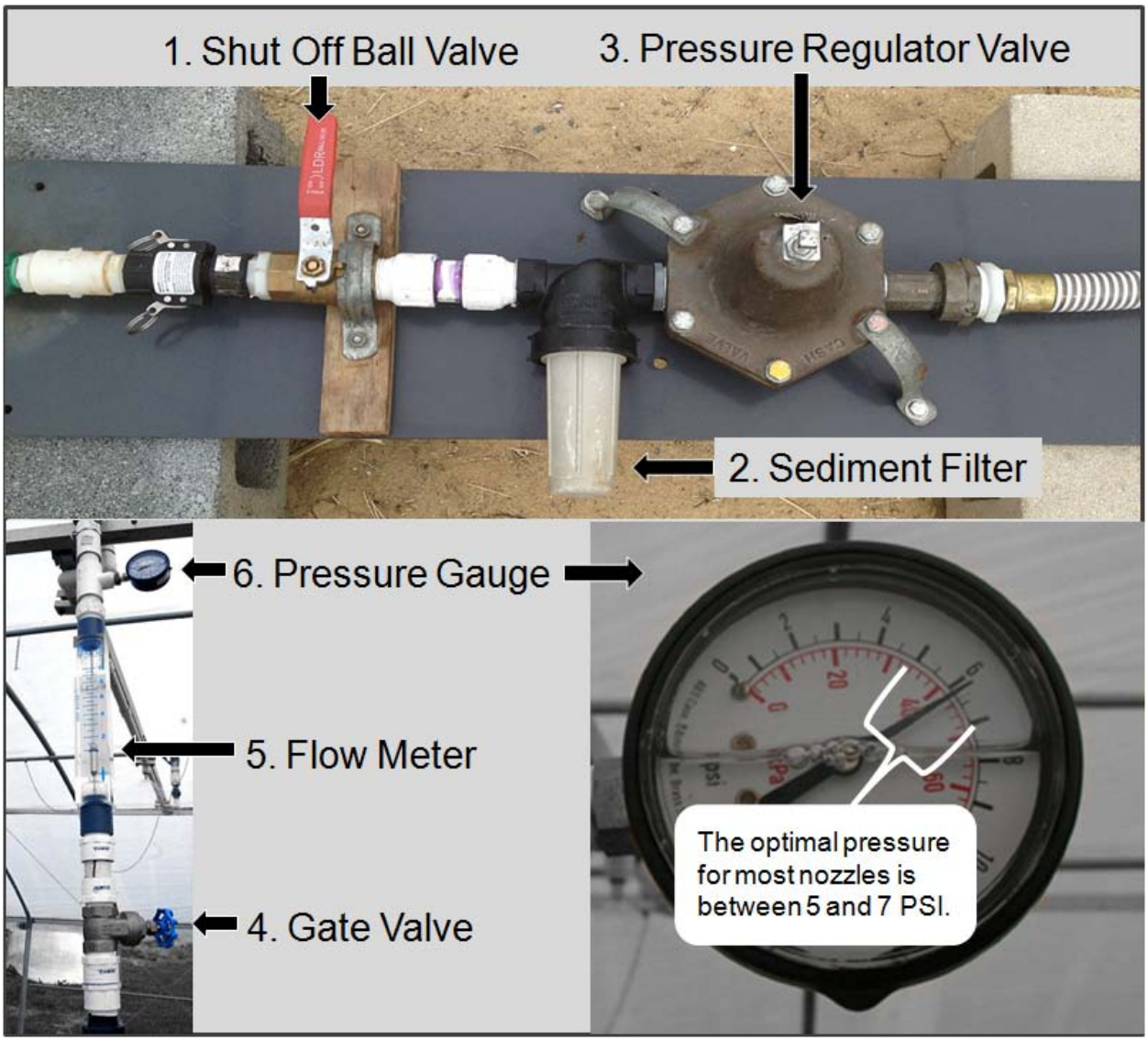

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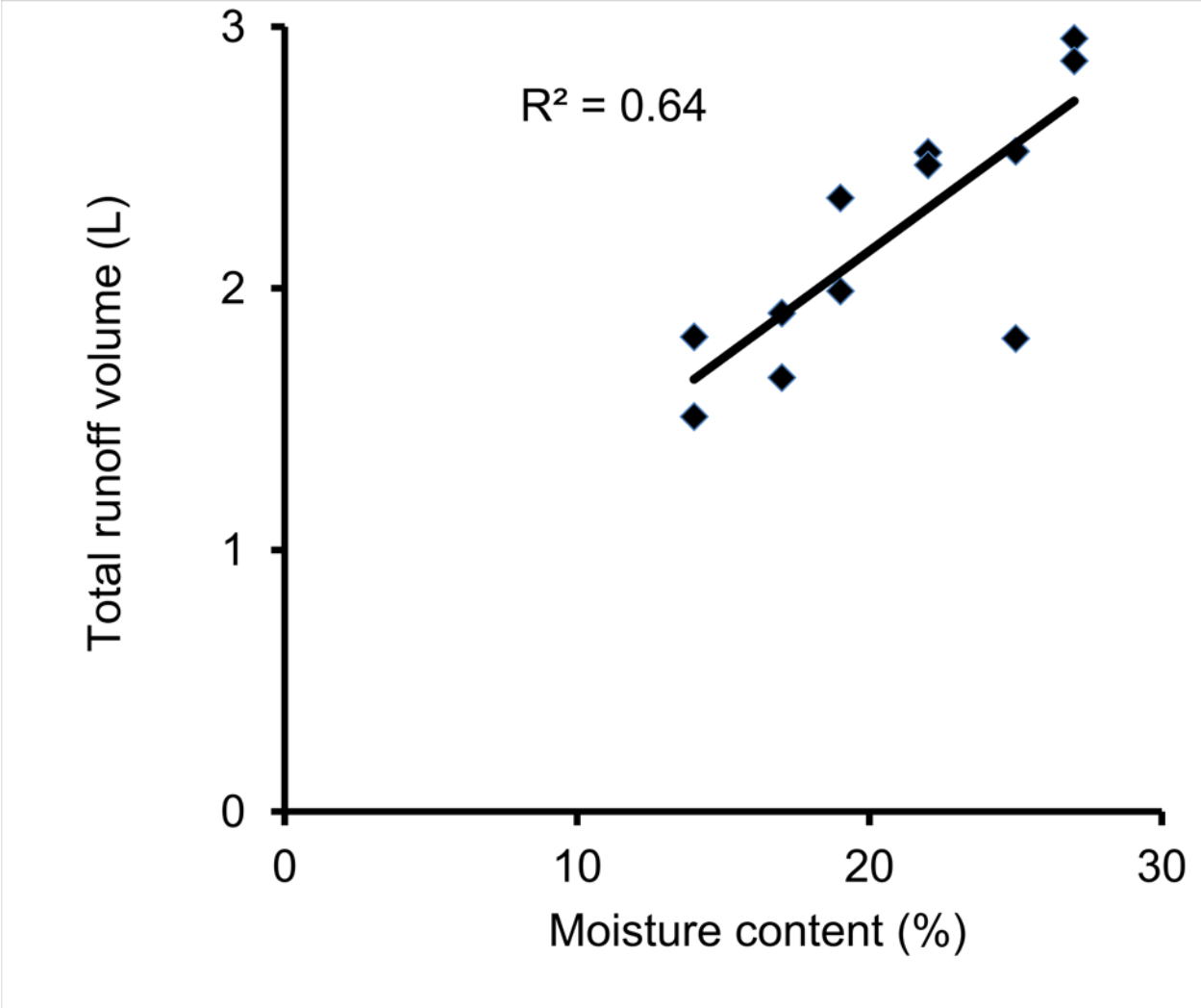

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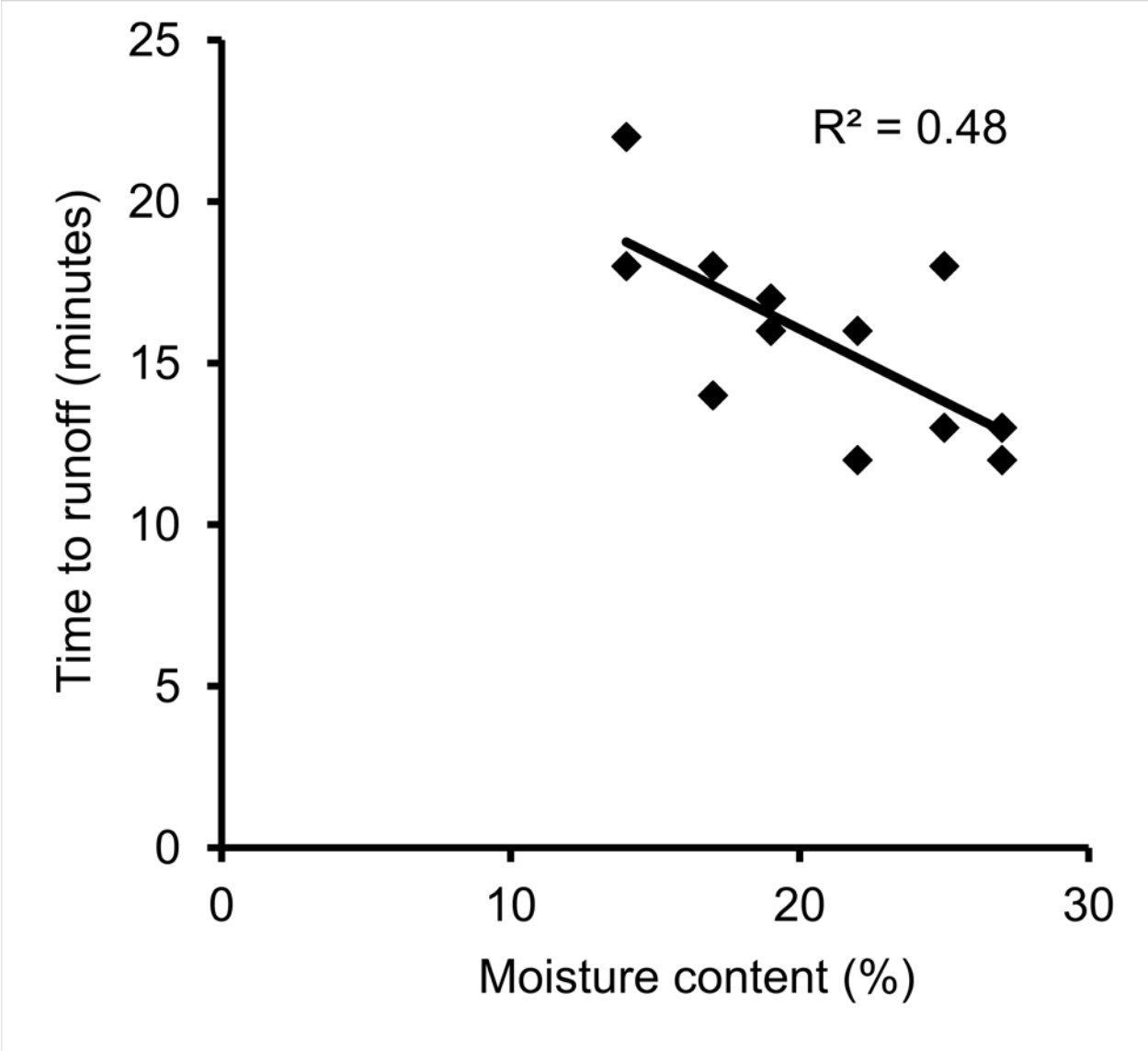

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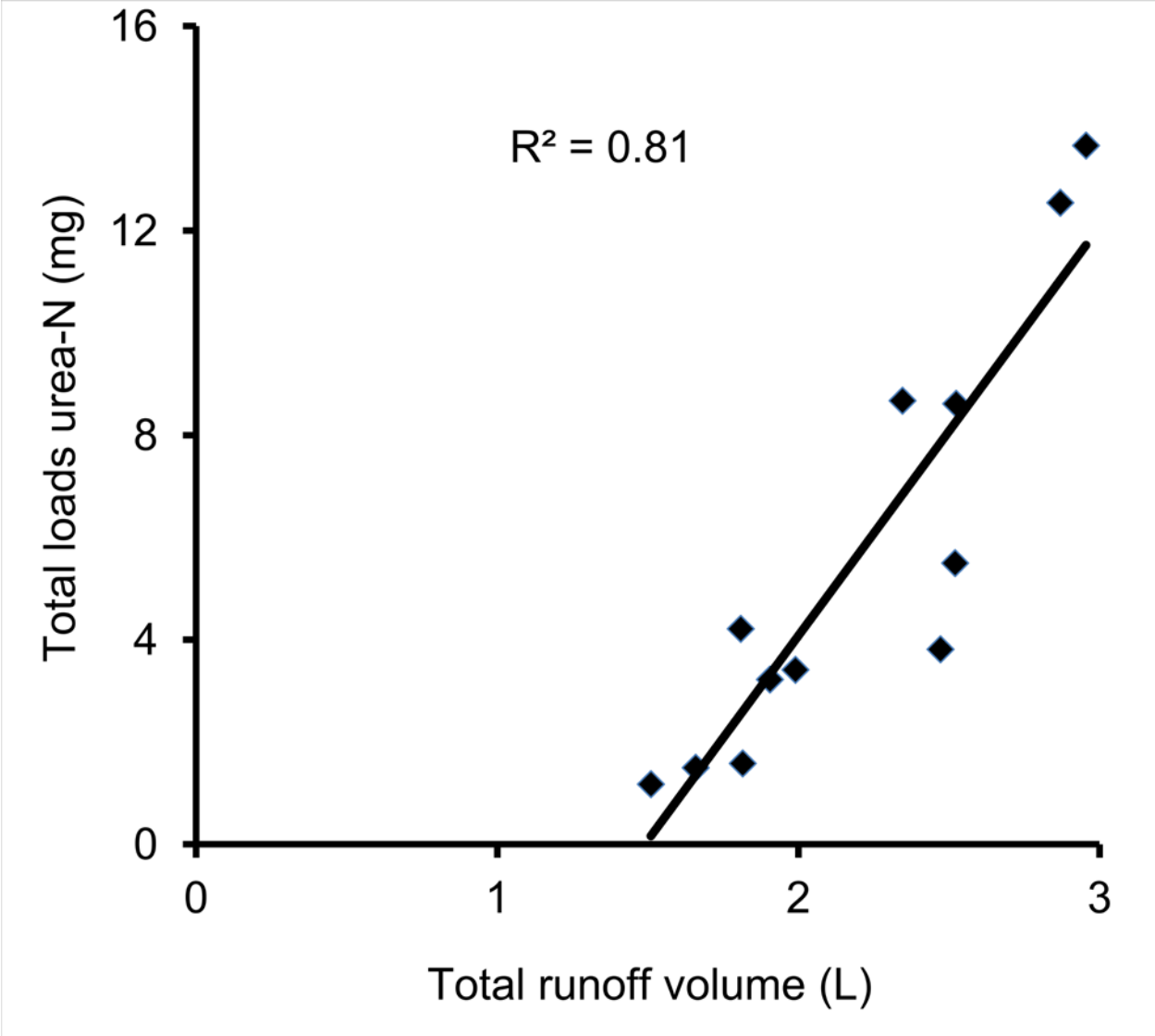

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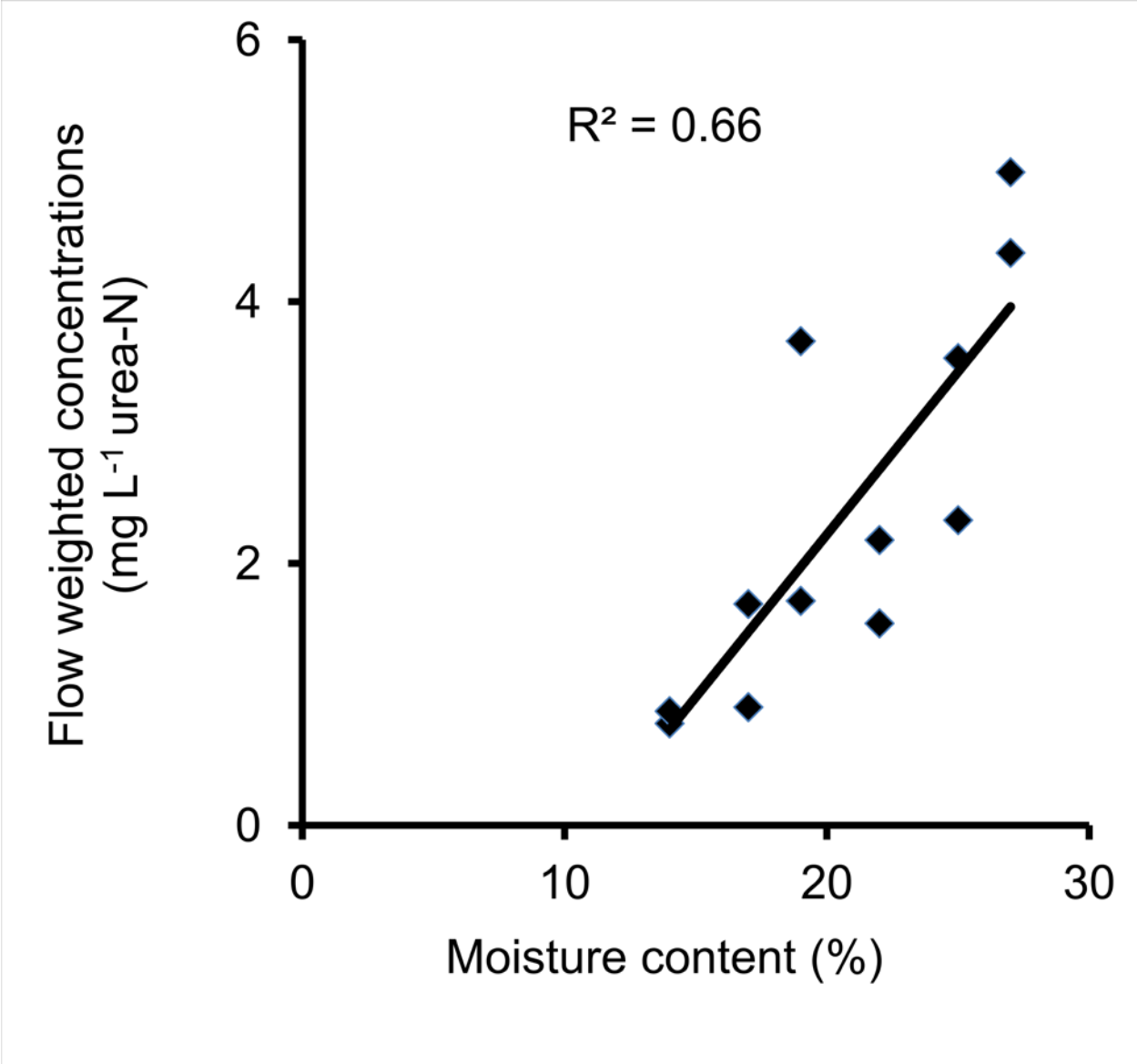

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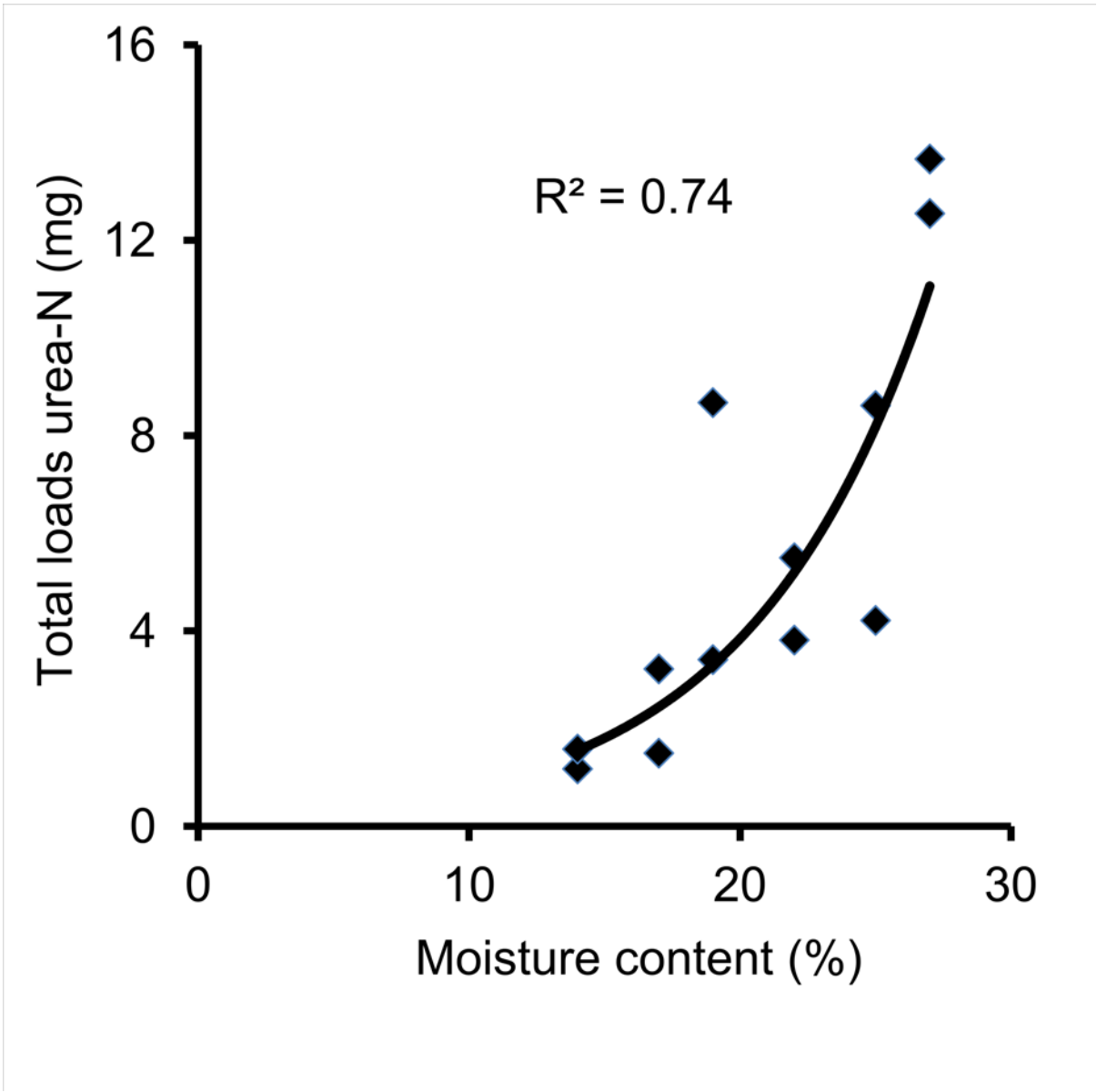

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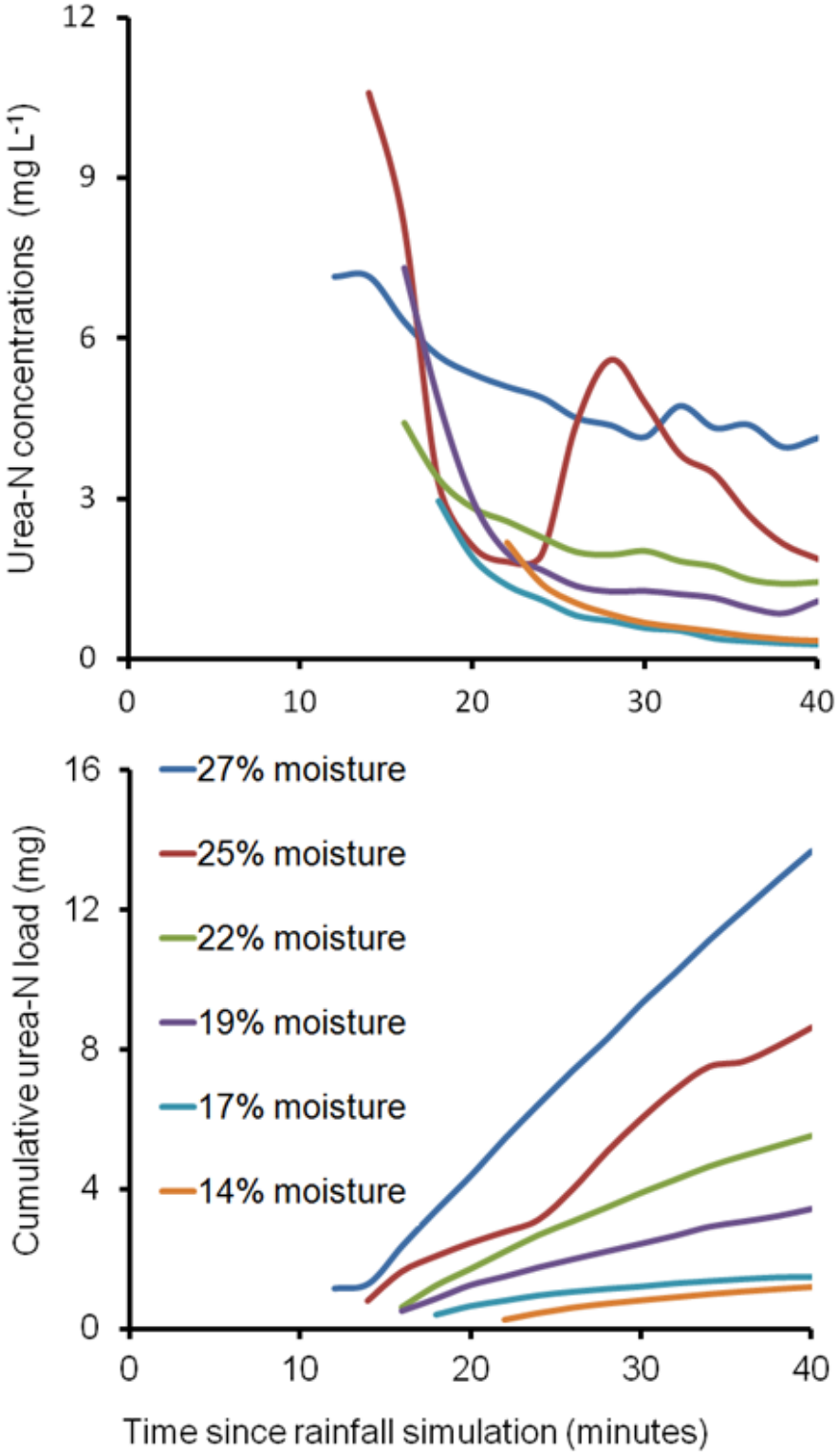

Table 1
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Table 1

Nozzle Size	Intensity cm hr^{-1}	Optimum Pressure psi	Flow gpm	10 sec. Flow ml
17 wsq Full Jet 3/8 HH	3.2	6.0	1.5	940
24 wsq Full Jet 3/8 HH	3.3	6.0	1.8	1140
30 w Full Jet 1/2 HH	6.0	5.0	2.2	1250
50 w Full Jet 1/2 HH	7.0	4.1	3.7	2300

Table 2
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Table 2

Soil moisture %	Total runoff volume (L)	Flow weighted concentration (mg L^{-1} urea-N)	Total load (mg urea-N)
27†	2.96	4.99	13.66
27	2.87	4.37	12.55
25	2.52	3.57	8.62
25	1.81	2.33	4.21
22	2.52	2.18	5.50
22	2.47	1.54	3.81
19	1.99	1.72	3.41
19	2.35	3.70	8.68
17	1.91	1.69	3.22
17	1.66	0.90	1.50
14	1.51	0.78	1.18

† Duplicate numbers represent two replications for each moisture level

*Excel Spreadsheet- Table of Materials/Equipment

Click here to download Excel Spreadsheet- Table of Materials/Equipment: RSP_Materials.xlsx

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
Rainfall Simulator	Joern's Inc.	TLALOC 3000	Size 1.5m x 2.0m (size optional)
Rainfall Simulator	Joern's Inc.	TLALOC 4000	Size 2.0m x 2.0m (size optional)
Rainfall Nozzle	Spraying Systems Inc.	3/8HH-SS17WSQ	Size 17 nozzle
Rainfall Nozzle	Spraying Systems Inc.	3/8HH-SS24WSQ	Size 24 nozzle
Rainfall Nozzle	Spraying Systems Inc.	1/2HH-SS30WSQ	Size 30 nozzle
Rainfall Nozzle	Spraying Systems Inc.	3/8HH-SS50WSQ	Size 50 nozzle

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Major Concerns:

Two global comments:

(a) The authors have used the word 'variance' numerous times; I think mostly incorrectly or inappropriately. I think the more general term 'variation' is what they mean, and thus should use. I have pointed out these instances in the manuscript. All occurrences of variance were changed to variation. This comment caused us to reevaluate our calculation of the coefficient of variation (CV). Changes were made to correct that discussion throughout the manuscript.

(b) The convention I know is for the dependent variable to be stated first followed by the independent variable. For instance, Runoff volume is related to antecedent moisture content. Not the other way round as the authors have stated numerous times. Numerous instances of such misuse (in my opinion) occur in the manuscript. Changes were made throughout the discussion section of the manuscript to conform with the recommended convention. Statements in the figure captions do conform to this convention.

Minor Concerns:

Because rainfall
79 simulators are designed to deliver raindrops of similar size and velocity as natural rainfall,
80 studies conducted under a standardized protocol can yield valuable data that, in turn, can be used
81 to develop models for predicting the fate and transport of pollutants in runoff. The part before the comma represents our wishful thinking as researchers. That point re rainfall is not necessary for the latter part of the sentence to be true.

85 in light of the uncertainties of global change. Is climate change meant? Global change is a broader term that refers to planetary-scale changes in the Earth system and encompasses the water cycle, the carbon cycle, the nitrogen cycle and other cycles. We think the term global change is more appropriate to our meaning.

102 Due to the unpredictability of natural rainfall, Variability is likely a better word than unpredictability.

We agree and changed the word.

107 constituents in runoff. When comparisons are made between natural rainfall and rainfall
108 simulation data, trends follow a similar pattern, pointing to a consistency in processes.
Perhaps reword to Trends between natural rainfall and rainfall simulation data follow a similar pattern, pointing to a consistency in processes. Sentence was reworded as suggested.
A reference or a few for this point (similar trend between rainfall and rainfall simulation) would be valuable as it is a key point.

114 Kentucky rainfall simulator, which covers a plot 14.75 feet by 72 feet (4.5 meters by 22 meters)
Revise to (4.5 m by 22 m) SI units are never spelled out (don't think feet are either) Changed both units

to abbreviations.

118 community of scientists from 11 participating countries concluded that a standardization of
119 rainfall simulation and simulators is needed....It seems like some statement from the authors at the end of line 120 as to what contribution their study makes to this great cause would be valuable.
Sentence was added as suggested.

147 150 top five cm of the surface. More correctly top 5 cm of the surface Corrected
162 165 results of the 6 samples have a coefficient of variance (CV) The authors mean coefficient of variation. Extensive edits to coefficient of variation discussions were made throughout.
171 174 and depth (100 cm x 20 cm x 7.5 cm) with nine 5mm drain holes in the bottom. Put a hyphen between 5 and mm Corrected

267 271 use (Table 1). Note: The 10 second flow volume is the most accurate measure for properly
268 calibrating the nozzle. That is a very short time period, why is it the most accurate? And what other volumes were used? Sentence was corrected to say that "For properly calibrating the nozzle, the 10 second flow volume is a more accurate measure than the reading on the flow meter."

277 282 7.7) Measure the volume of water (ml) use mL instead to avoid confusion with the number 1 corrected

281 286 7.8) Calculate the coefficient of variance see note above Corrected
324 330 runoff. This order of magnitude variance.... again maybe variation in a general sense rather than variance? Corrected
330 336 In order to investigate the cause for such extreme variance, see immediately preceding comment...also is the extreme variance referring to the values given in line 323? Perhaps state such extreme variation in what...Clarified
332 338 to minimize variance in physical conditions. Ditto re variance
Corrected
332 338 to minimize variance in physical conditions. To achieve 50, 60, 70, 80, 90, and 100 % of field
333 339 capacity, the weight of water required to wet the soil to corresponding antecedent soil moistures
334 340 of 14, 17, 19, 22, 25 and 27 % was calculated, added to the boxes, and allowed to equilibrate
335 341 overnight.
These values are highly soil texture specific. The authors have not mentioned what soil texture they were using, undoubtedly the greatest factor of all affecting infiltration. Soil texture was added on line 338.

333 340 how was field capacity determined? Give a reference or explain. Explanation was provided.

337 344 intensity of 3.2 cm hr-1 over a 40 minute period. How were these two critical parameters chosen? Explanation provided.

340 348 Table 2. There was a significant positive relationship between antecedent moisture condition and
341 349 total runoff volume (Figure 6).
Total runoff volume depends on antecedent moisture condition, not the other way round. So the relationship is between total runoff volume and antecedent moisture conditions (dependent variable given first). Changed to conform with this convention throughout the manuscript.

341 total runoff volume (Figure 6). Wetter soils had less capacity to store water resulting in greater
342 351 runoff volumes.
Technically true but not actually. The issue isn't really storage. Wet soils have lower infiltration rates than dry soil do...that is why there is greater total runoff volume under wet soils than dry ones. Water not infiltrated runs off. Sentence was edited to say both: less capacity to store water and lower infiltration rate.

342 352 runoff volumes. There was a significant negative relationship between antecedent moisture
343 353 condition and time to runoff (Figure 7). Water infiltrated into drier soils for a longer period of
344 354 time before they became wet near the surface, causing runoff to occur. Not surprisingly, there
345 355 was a positive relationship between total runoff volume and total load urea-N in runoff
Two more instances where the variable order needs to be reversed...give the dependent ones first
Changed to conform with this convention throughout the manuscript.

364 375 runoff is longer and urea-N concentrations in runoff are lower for drier soils. Worth mentioning what the trend in loads was? Yes, sentence was modified to include effects on load.

458 470 all boxes, consider grouping replicate treatments within individual runs to minimize variance again variation might be a better word Corrected

I Suggest that authors consider the extensive review referenced by Grismer, rather than the abbreviated summary in Cal Ag. We did locate a 110 page report that was presented at TSC Rainsim workshop 4 March 2011. However, that was labeled draft, and we considered it to be gray literature. Grismer does not reference that report in his Cal Ag paper. It appears that Grismer considers the Cal Ag peer-reviewed paper to be his published work, so we choose to cite the Cal Ag paper.

Additional Comments to Authors:
Fabulous job!
Thank you for your very helpful and constructive comments.

Reviewer #2:
Manuscript Summary:

N/A

Major Concerns:
The paper format is unusual for me and appears to be an operations manual, rather than a research paper. However, the methods, results and the like are clearly outlined as a result. This is a function of the journal format requirements for a paper whose purpose is to describe an experimental method in detail. It is quite different from most reports of a scientific study.

The authors might want to consider the number of other papers that deal with the same matter using greenhouse sandbox RS studies by Kinnel, Lui (1998) and others. My greatest concern in the methods section is the 5 cm soil/sand depth is inadequate and would likely lead to far greater runoff rates than encountered in the field. Although greater soil depth may better approximate field conditions, this depth has been widely accepted as the standard for these studies. The key is that "Trends between natural rainfall and rainfall simulation data follow a similar pattern, pointing to a consistency in processes." (Line 108)

I appreciate the effort towards developing a standard method as pointed out

And we appreciate the time and effort that both reviewers devoted to the improvement of this manuscript.

Minor Concerns:
N/A

Additional Comments to Authors:
N/A

Your revision is due by **Nov 27, 2013**.

To submit a revision, go to the *JoVE* submission site and log in as an author. You will see a menu item called 'Submission Needing Revision'. You will find your submission record there.

Sincerely,

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