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Article

Modeling nutrient losses in an Oxisol under different management systems and rainfall events

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ABSTRACT: This study aimed to model nutrient losses in an Oxisol under varied soil properties and vegetation cover. The experimental area was located at the Paraná Rural Development Institute, in Santa Tereza do Oeste, Paraná, Brazil. The treatments consisted of six cover crops in summer, six cover crops in winter, and management systems no-tillage (NT) traditional (control), NT with gypsum, and NT with scarification. Nutrient data were collected at each natural rainfall through sample collection from collection troughs. The design was completely randomized, and the data were adjusted using an exponential function of two variables, as a function of soil density, macroporosity, straw dry mass, green cover, and rainfall. Greater losses of Mg and Ca was related to higher soil density and lower macroporosity. Lower losses of Mg, Ca, K, and P were associated with lower straw dry mass and higher green cover. K and P losses were stable for all soil density values, but they decreased with an increase in macroporosity.

Key words: water erosion, models, optimization.

INTRODUCTION

Grain production requires an increasing use of technology and improvements in soil management from rural producers. In 2018, the National Supply Company (CONAB) estimated that the 2017-2018 harvests in Brazil produced 111,558.6 thousand tons of soybeans, ranking second highest in the global grain production. Soybean production in Paraná ranks second highest of Brazilian states, with an estimated production of 18,307.1 thousand tons (CONAB 2018).

Despite high production in Brazil, aspects of soil management (such as water erosion) are concerning for future grain production. Water erosion drags soil particles by surface runoff, causing loss of water, soil, and nutrients. Causes of water erosion can be natural or human (Marioti et al. 2013), and the soil properties influence the propensity for erosion. The consequences of erosion include decrease in soil fertility, reduction in productive potential, increase in fertilizer costs, the impracticability of production areas, siltation, and decrease in the availability of water for crops (Marioti et al. 2013; Candido et al. 2014). Changes to the soil characteristics, which usually occur during agricultural practices, should therefore be mitigated by environmental management (Ouyang et al. 2018).

Several studies related to soil, water, and nutrient losses have contributed significantly to our understanding of erosion and strategies for soil conservation practices, generally using patterns under simulated or natural rainfall (Miguel et al. 2014). Consequently, a variety of soil erosion models have been developed and presented as mathematical expressions that characterize individual processes (Pandey et al. 2016).

Research has shown that the main method of nutrient loss is water runoff (Oliveira et al. 2015, Adviento-Borbe et al. 2018). Thus, soil impoverishment is linked to sediment transport and soil slope (Mendonça et al. 2015). Bramorski et al. (2015) evaluated nitrogen losses resulting from water erosion and found that the loss of nutrients negatively affects the quality of surface and groundwater. Dechen et al. (2015) analyzed uncovered soils and estimated that 16% P_2O_5 and 8% KCl were lost compared to the recommended fertilizer rate for the crop. Huo et al. (2021) reported that the factors positively impacting soil nutrient loss were runoff (44–48%), maximum rainfall intensity over a 30-min period (18–29%), rainfall depth (20–27%), and soil loss (10–14%). Li et al. (2023) revealed that the total rainfall and rainfall duration were the primary factors that determined the levels of runoff, soil erosion, and the associated nutrient losses.

It was hypothesized that nutrient losses were influenced by crop rotation and management and that high nutrient losses occurred due to high rainfall intensities in compacted soils. We therefore suggest there is a gap in our knowledge related to losses under different management systems. In this study, we aimed to model nutrient losses in an Oxisol. We explored the effect of different management systems that vary the physical attributes of the soil and vegetation cover.

MATERIAL AND METHODS

Study area

The study area is located at the Paraná Rural Development Institute (IDR-Paraná), a regional center in Santa Tereza do Oeste, Paraná, Brazil (53°29'37"W, 24°50'42"S, and 607 m a.s.l.). According to the Köppen classification, the region has a humid subtropical climate with a mean annual rainfall of 1,840 mm. The local relief gently undulates, and the slope varies from 0.21 to 5.41%. The experiment was carried out during the 2017/2018 harvest, and the soybean crop was grown on crambe straw by the practice of no-till.

The soil of the experimental area was classified as Oxisol (Soil Survey Staff 2014), with 60% clay, 4% sand, and 36% silt in the top 20 cm. Other soil properties were pH in $CaCl_2$ of 5, 24.8 $g \cdot dm^{-3}$ of soil organic carbon (SOC), 25.3 $mg \cdot dm^{-3}$ of P (Mehlich-1), 0.50 $cmol_c \cdot dm^{-3}$ of K, 4.90 $cmol_c \cdot dm^{-3}$ of Ca, 2.50 $cmol_c \cdot dm^{-3}$ of Mg, and 52% of soil base saturation.

Treatments and experimental design

Our experimental design consisted of 15 plots, in which vegetation was planted after soybean cultivation, six in summer, six cover crops in winter, and management systems no-tillage (NT) traditional (control), NT with gypsum, and NT with scarification (Table 1).

Table 1. Fifteen first treatments of the experiment.

Cover crops/summer
Millet - *Pennisetum americanum*
Pigeon pea - *Cajanus cajan*
Sunn hemp - *Crotalaria juncea*
Sunn hemp - *Crotalaria spectabilis*
Pigeon pea dwarf - *Cajanus cajan*
Velvet bean - *Mucuna pruriens*
Cover crops/winter
White oat - *Avena sativa*
Black oat - *Avena strigosa*
Rye - *Secale cereale*
Black oat + forage turnip - *Raphanus sativus*
Black oat + white lupine - *Lupinus albus*
Black oat + group pea - *Pisum arvense*
Use and management systems
NT system with scarification
NT with application of 3 $t \cdot ha^{-1}$ of gypsum on surface
Traditional NT (control)

NT: no-tillage.

A compressed range was determined for all treatments, except T5, to increase the data available for curve fitting. Thus, 29 treatments were included in our fitting analysis. For runoff collection, 29 polyvinyl chloride collector gutters were built (Fig. 1): one for each treatment, with areas of 9 m^2 (3 × 3 m) delimited by grass separators. The gutters were placed along slope so that water could drain into 25 L containers via 3/4" corrugated hoses. Natural rainfall events throughout the soybean rainfall cycle were analyzed.

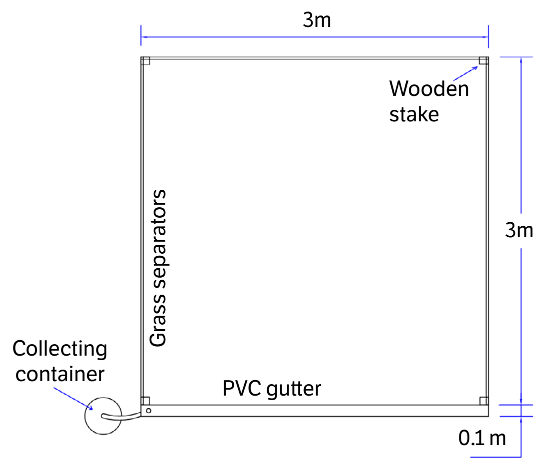

Figure 1. Model of collector gutters and their measurements.

Determination of physical properties

Undisturbed soil samples were collected before sowing and after harvest at three depths (0–0.1, 0.1–0.2, and 0.2–0.3 m). Soil density (SD), macroporosity (Ma), microporosity (Mi), and total porosity (TP) were analyzed. Trenches 30-cm wide, 40-cm long, and 30-cm deep were opened in each plot. The samples were capillary saturated and subjected to the tension of 6 kPa on a sand column (Reinert and Reichert 2006). Finally, the samples were dried at 105 °C to a constant weight to determine SD. The TP was calculated from the SD and particle density (PD) values (TP = 1- (SD/PD)). Mi was calculated based on the volume at 6 kPa tension, while Ma is the difference between TP and Mi. The Mi had little variation and was not presented.

Nutrient collection

We collected nutrients on 20 occasions between Aug. 11, 2017, and Oct. 2, 2018 (Fig. 2), recording the time of day for collection in each case. We stored the collected material in containers and then homogenized and quantified the material using graduated cylinders. We then removed 500 mL of material from the polyethylene terephthalate (PET) bottles. To quantify nutrient loss, the concentrations of P, K, Ca, and Mg were analyzed in each sample and determined according to the methodology recommended by Embrapa (1997).

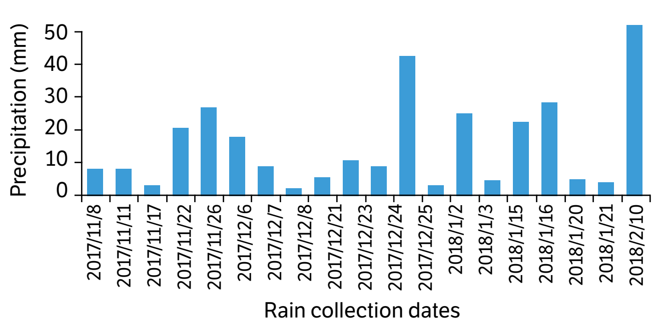

Figure 2. Accumulated precipitation during the days of collection.

Straw collection and green cover

Plant residue was collected every 15 days. We used a quadrangular frame measuring 30 × 30 cm, with two repetitions per plot. The material was collected in Kraft paper bags. The straw samples were weighed after being placed in an oven at 65°C until they reached a constant mass.

To collect green cover, two random points were selected per plot, and a quadrangular frame of 1 m^2 was placed on top of the soybean leaf cover. Photos of this area were digitally cropped and then processed by Canopeo (Mathworks, Inc., Natick, MA, United States of America), which calculates the percentage of leaf area (Patrignani and Ochsner 2015).

Statistical analysis

Measures of central tendency were calculated in R (R Core Team 2019), while Microsoft Excel was used for curve fitting for straw and green cover.

Mathematical modeling

Models of nutrient loss were adjusted as a function of SD, Ma, SDM, green cover (Cov), and rainfall intensity (Int). The Statistica software (Version 7.0, StatSoft Inc., Tulsa, United States of America) was used to calculate the fit parameters. The Levenberg–Marquardt method was implemented to optimize the nonlinear least squares fit.

The loss of nutrients (nutrients loss) was adjusted using an exponential function of two variables (Eq. 1):

$$\textit{Nutrients loss } (Int,f) = a \exp (b \cdot Int) + c\, f + d \tag{1}$$

where: *Int*: the maximum rainfall intensity for each precipitation event; *f*: a physical parameter known through field observations to be considered in the modeling (SD, Ma, Cov, and SDM); *a, b, c* and *d*: fitting constants.

For SDM, the least squares method was used to estimate the values for each collection day through a third-degree polynomial function (Eq. 2):

$$Sdm(t) = at^3 + bt^2 + ct + d \tag{2}$$

where: *t*: the number of days after sowing.

A third-degree polynomial was used because it showed a good coefficient of determination that captured a representative trend as a function of time (Fig. 3).

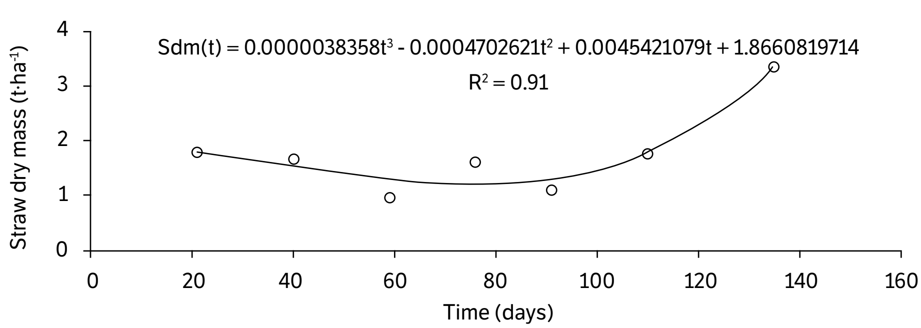

Figure 3. Example of straw dry mass (Sdm) submodel throughout the soybean cycle. The observed data is represented by the points, while the trendline is the result of the equation shown in the article.

Green cover is presented as a percentage, whose values were estimated for each day of collection. The coverage was 0% on the day of sowing and on the day of complete drying of the leaves (135 days after sowing). Mathematically, it is represented as Eq. 3:

$$Cov(0) = Cov(135) = 0 \tag{3}$$

where: Cov(t): the percentage of green cover over time, t.

To ensure that no estimate exceeds 100%, the following is defined (Eq. 4):

$$0 \leq Cov(t) \leq 100 \tag{4}$$

We found that the combination of two different polynomial degrees better represented the data (Fig. 4). Therefore, we chose to use a function defined by parts, as follows (Eq. 5):

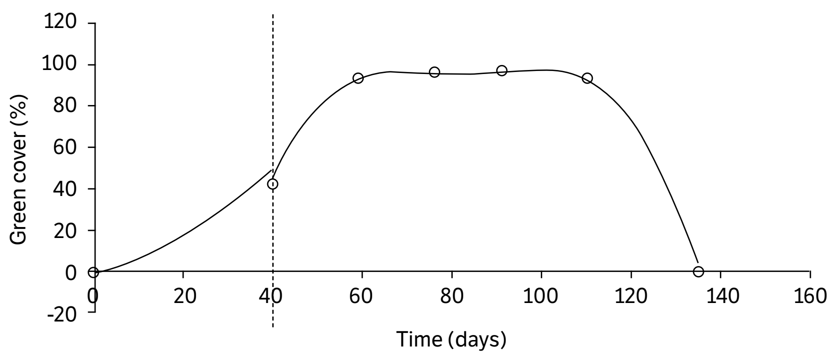

Figure 4. Example of submodel for green cover using piecewise defined function.

$$Cov_\tau(t) = \begin{cases} \sum_{i=0}^{n_1} a_i t^i, & t < 40 \\ \sum_{i=0}^{n_2} b_i t^i, & t \geq 40 \end{cases} \tag{5}$$

where: τ: the treatment number; n_1: the degree of the polynomial referring to the model before the 40th day; a_i and b_i: the parameters adjusted to the data; n_2: the degree of the polynomial referring to the model after the 40th day.

RESULTS AND DISCUSSION

Descriptive statistics

Table 2 presents the descriptive statistics of nutrient losses for all treatments and collection days. The averages represent the approximate losses for each treatment and the rain collection.

The coefficient of variation was high for all nutrients, showing its heterogeneity (Table 2). The p-values of the analysis of variance was > 0.05, so no significant differences were identified in the loss of nutrients, which can be explained by the good soil structure present in the experimental area.

Table 2. Descriptive statistics of nutrient losses.

	Mg ($kg \cdot ha^{-1}$)	Ca ($kg \cdot ha^{-1}$)	K ($kg \cdot ha^{-1}$)	P ($kg \cdot ha^{-1}$)
Min.	$4.09 \cdot 10^{-6}$	0.00061	0.00629	0.0002613
Q1	$1.96 \cdot 10^{-3}$	0.00713	0.0629	0.001919
Q2	$3.81 \cdot 10^{-3}$	0.01542	0.1401	0.004095
Average	$9.47 \cdot 10^{-3}$	0.04369	0.5459	0.1026
Q3	$9.32 \cdot 10^{-3}$	0.04565	0.3321	0.008597
Max.	$7.08 \cdot 10^{-2}$	0.57980	11.19	0.2356
S	$1.69 \cdot 10^{-4}$	0.06996	1.526011	0.022775
S^2	$1.37 \cdot 10^{2}$	0.00489	2.32871	0.00052
CV (%)	137,336	160.15250	279.5493	221.9226
Ass.	100,300	1.21221	0.79777	12.97559
K	0.122	0.16119	0.36064	0.19506
ANOVA (p-value)	0.9925	0.7196	1.0000	0.9998

Min.: minimum; Q1: first quartile; Q2: second quartile or median; Q3: third quartile; Max.: maximum; S: standard deviation; S2: variance; CV: coefficient of variation; Ass.: asymmetry; K: kurtosis; ANOVA: analysis of variance.

Models

Mg loss

The models generated for Mg loss are presented in Table 3. The function dependent on SD and Ma presented values close to R^2, as well as in the function that considered straw dry mass and green cover. This shows the extent to which both parties are associated.

Table 3. Mg, Ca, K, and P loss models as a function of maximum rainfall intensity per precipitation event ($mm \cdot h^{-1}$), soil density ($g \cdot cm^{-3}$), macroporosity (%), straw dry mass ($t \cdot ha^{-1}$) and cover vegetable (%).

Equations	R^2
$Mg\ loss(Int,SD) = 32.4067\ exp(3.92 \cdot 10^{-5}\ Int) + 0.01342\ Ds - 32.421$	0.4145
$Mg\ loss(Int,Ma) = 30.0883\ exp(4.22 \cdot 10^{-5}\ Int) - 3.8 \cdot 10^{-4}\ Macro - 30.082$	0.4153
$Mg\ loss(Int,Sdm) = 38.4991\ exp(3.42 \cdot 10^{-5}\ Int) + 8.4 \cdot 10^{-4}\ Sdm - 38.5$	0.5409
$Mg\ loss(Int,Cov) = 36.5216\ exp(3.6 \cdot 10^{-5}\ Int) + -2.2 \cdot 10^{-5}\ Cov - 36.52$	0.5422
$Ca\ loss(Int,SD) = 81{,}9488\ exp(7.96 \cdot 10^{-5}\ Int) + 0.088132\ Ds - 82.045$	0.3626
$Ca\ loss(Int,Ma) = 79.3407\ exp(8.22 \cdot 10^{-5}\ Int) - 0.00333\ Macro - 79.295$	0.3660
$Ca\ loss(Int,Sdm) = 90.7954\ exp(7.23 \cdot 10^{-5}\ Int) + 0.004049\ Msp - 90.802$	0.4716
$Ca\ loss(Int,Cov) = 79.3833\ exp(8.25 \cdot 10^{-5}\ Int) - 1.8 \cdot 10^{-3}\ Cov - 79.369$	0.4776
$K\ loss(Int,SD) = 1501.67\ exp(5.19 \cdot 10^{-5}\ Int) - 0.00695\ Ds - 1501.7$	0.1077
$K\ loss(Int,Ma) = 1450.35\ exp(5.37 \cdot 10^{-5}\ Int) - 0.01452\ Macro - 1450.2$	0.1079
$K\ loss(Int,Sdm) = 1325.66\ exp(5.85 \cdot 10^{-5}\ Int) + 0.209262\ Sdm - 1326.0$	0.1676
$K\ loss(Int,Cov) = -2.1242\ exp(-0.06199\ Int) - 0.00131\ Cov + 2.16698$	0.1721
$P\ loss(Int,SD) = 21.9236\ exp(5.01 \cdot 10^{-4}\ Int) - 0.00445\ Ds - 21.916$	0.0957
$P\ loss(Int,Ma) = 23.1815\ exp(4.73 \cdot 10^{-5}\ Int) - 3.5 \cdot 10^{-4}\ Macro - 23.175$	0.0962
$P\ loss(Int,Sdm) = 31.3146\ exp(3.9 \cdot 10^{-5}\ Int) + 0.002738\ Sdm - 31.318$	0.1765
$P\ loss(Int,Cov) = 31.0742\ exp(3.93 \cdot 10^{-5}\ Int) - 2.7 \cdot 10^{-4}\ Cov - 31.071$	0.1702

Int: maximum rainfall intensity per precipitation event; SD: soil density; Ma: macroporosity; Sdm: straw dry mass; Cov: green cover.

Mg losses increased with increasing SD (Fig. 5). Bertol et al. (2017) evaluated nutrient losses due to water erosion and found that Mg is highly sensitive to the effects of soil management and the type of crop in the surface soil layer. Mg is an essential element for chlorophyll production, and prolonged Mg loss can result in soil degradation (Wang et al. 2018). Therefore, it is necessary to pay attention to soil management strategies that interfere with soil compaction, because SD increase can lead to nutrient loss.

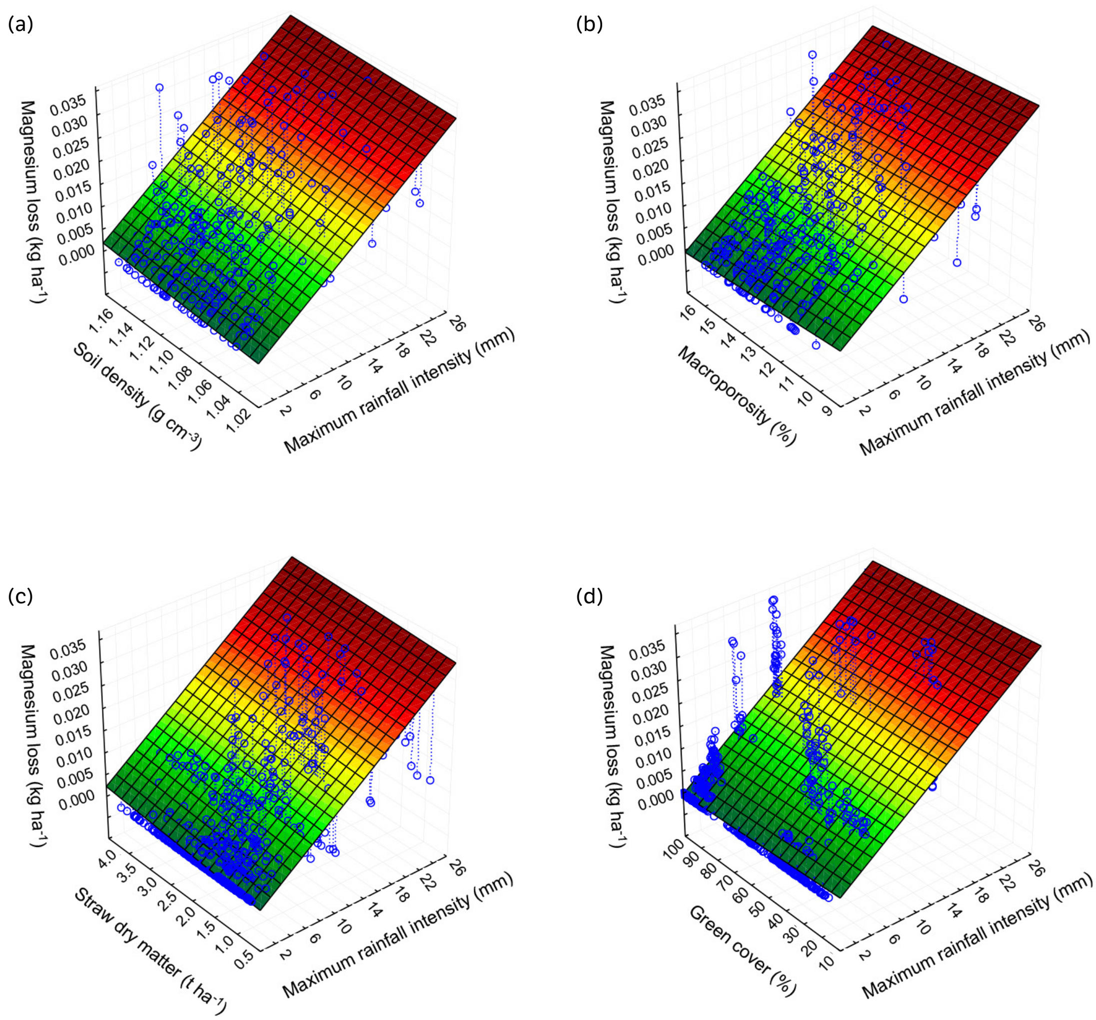

Figure 5. Magnesium loss affected by (a) soil density, (b) macroporosity, (c) straw dry mass, and (d) green cover.

We also observed reduction in Mg loss with increasing Ma (Fig. 5). Therefore, the greater the pore volume in the soil profile, the lower the Mg loss. We also observed an increase in Mg loss with increasing straw dry mass. This can be verified by adjustment according to green coverage. The same behavior of the graphs generated, combined with values close to R^2, shows the integrated effect of straw and mulch on Mg loss.

As highlighted by Bertol et al. (2003), variations in waterborne Mg concentrations due to erosion processes are significantly shaped by the soil management systems adopted. The amount of Mg lost through water erosion was positively correlated with the degree of soil fertilization and increased soil tillage intensity. Through a comprehensive assessment of Mg loss via water runoff under simulated rainfall conditions, researchers have shown that substantial Mg concentrations in eroded water are associated with conventional tillage practices.

Ca loss

The models generated for Ca loss are listed in Table 3. They show a clear relationship between Ca loss and Ma, dry mass of straw, and green cover. The opposite signs of the coefficients for both relations show that they are inversely proportional.

Figure 6 illustrates the shifts in losses relative to the assessed variables. The results revealed that the most substantial nutrient losses coincided with increased SD and decreased Ma values. The susceptibility of Ca to soil management strategies and crop selection were observed particularly in the uppermost soil layers (Bertol et al. 2017; Borgmann et al. 2021). Ca shows high susceptibility to erosional sediment conveyance, owing to its affinity for absorption onto soil colloids (Oliveira et al. 2015).

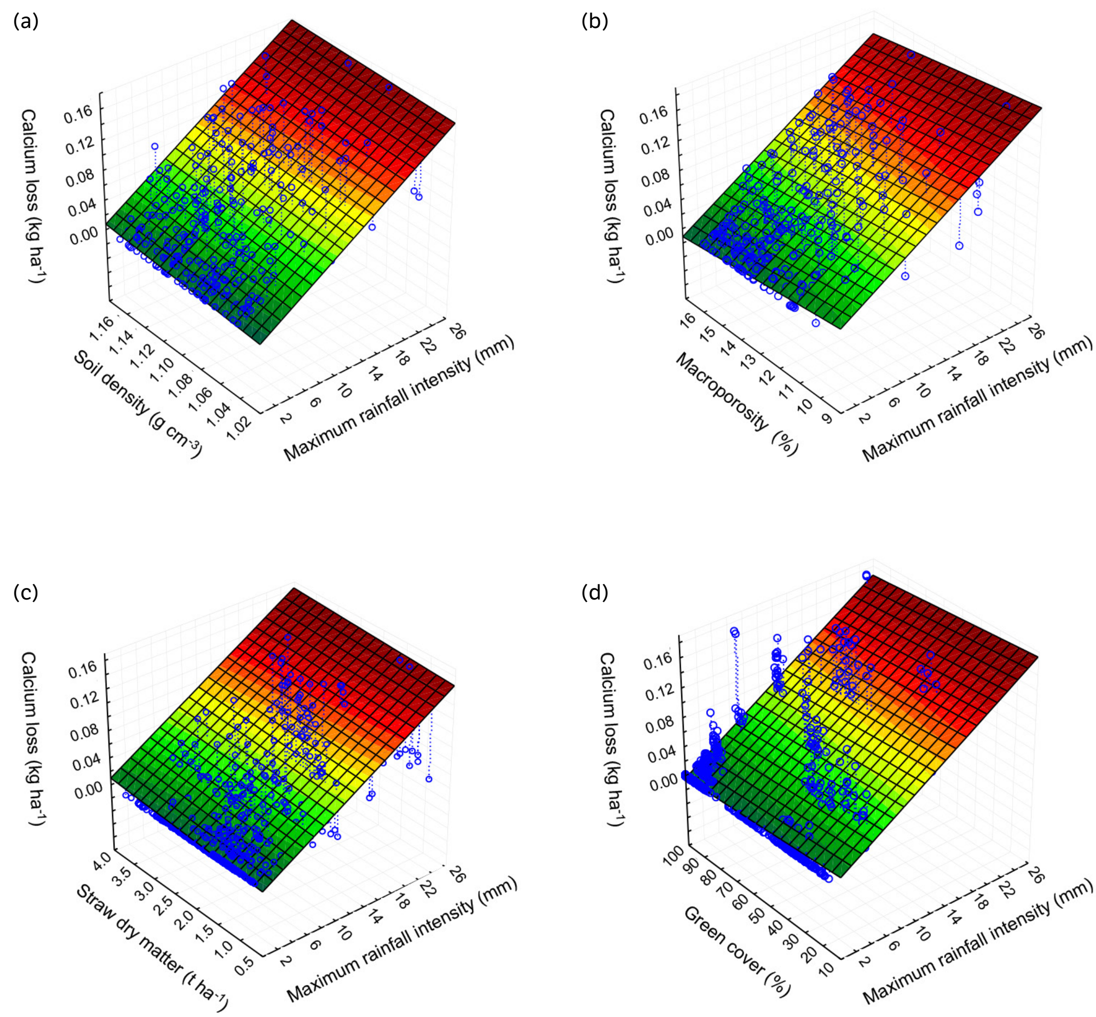

Figure 6. Calcium loss affected by (a) soil density, (b) macroporosity, (c) straw dry mass, and (d) green cover.

The study conducted by Bertol et al. (2003) revealed that Ca was considerably lost through water erosion, possibly owing to the elevated solubility of the element in water; this is further compounded by its propensity for elevated concentrations within the soil matrix. Wang et al. (2019) reported that soil acidification potentially increased surface Ca loss through runoff mechanisms.

Analysis of Ca loss as a function of the dry mass of the straw and the green cover showed opposite relationships, in which there was an increase in Ca loss with a decrease in straw and an increase in green cover. We found that the green coverage data were dispersed, which can be explained by the homogeneity of the green cover data on certain collection dates.

K loss

The models generated for K showed unusual behavior, since the coefficient in the P(Int, Cov) equation was negative. This is represented by the exponential curve in Table 3. This result is physically problematic, because it means that K losses at rainfall intensities greater than those proposed in this work will be limited by the horizontal asymptote. K losses were stable with variations in SD (Fig. 7), and there was reduction in K loss with increase in Ma. Since K is a mobile element, it is very susceptible to leaching (Kaufmann et al. 2019), which can interfere with laminar flow losses. Leaching, defined as the loss of nutrients by water transport in the soil profile, is facilitated in soils with greater Ma.

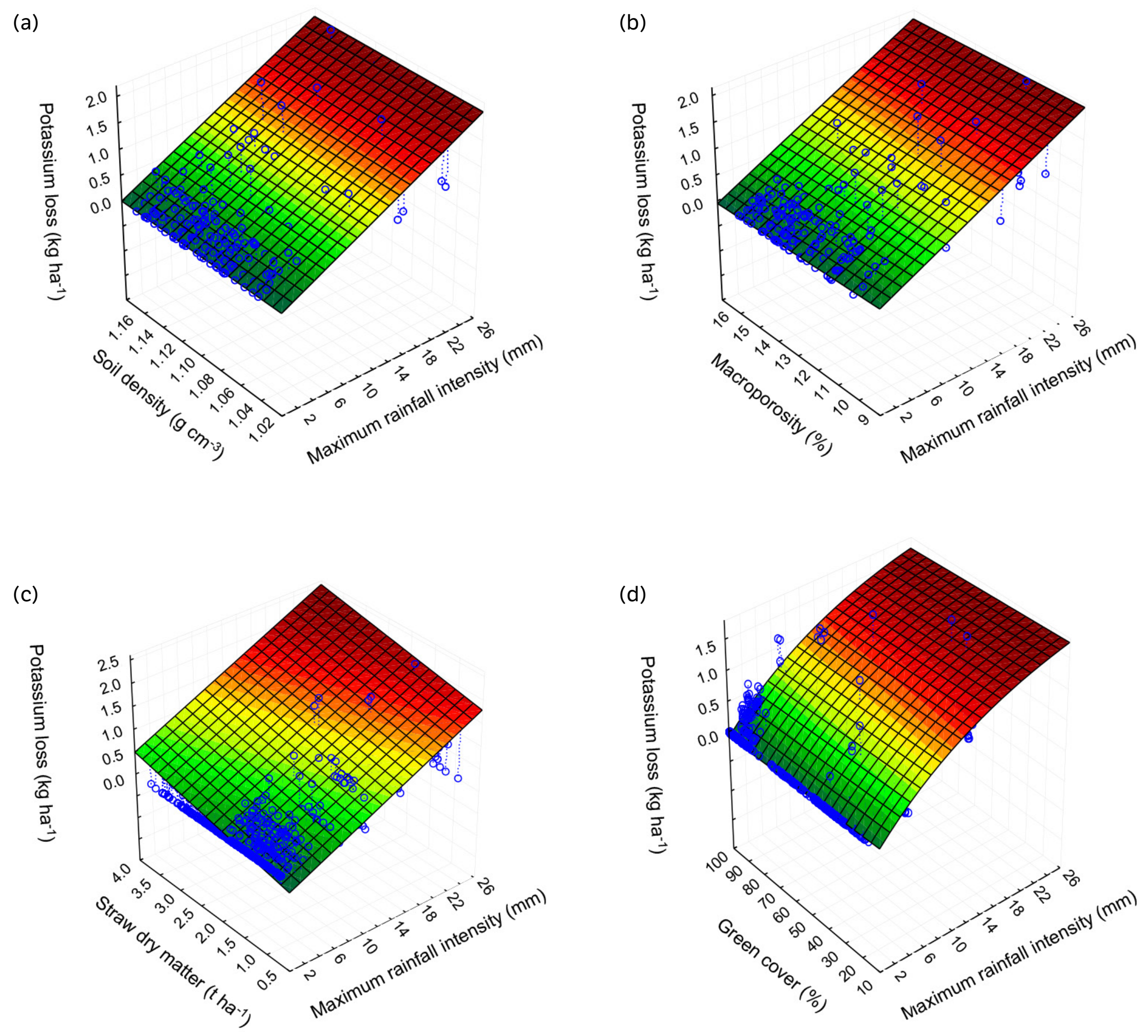

Figure 7. Potassium loss affected by (a) soil density, (b) macroporosity, (c) straw dry mass, and (d) green cover.

Regarding nutrient loss as a function of straw dry mass, the highest losses were associated with straw dry mass. This contradicts the results of Leite et al. (2018), who evaluated nutrient loss in the context of natural rainfall. The authors found that the lowest K losses occurred in systems with greater conservation of vegetation cover. This can be explained by the combination of straw and green cover in our study. We also observed lower K losses with higher green cover. This differs to the results from Bosch et al. (2015), who found that erosion-induced K loss did not differ between treatments with exposed soil and vegetation cover.

Based on the study conducted by Bertol et al. (2011) on the overall concentration of K within the runoff from simulated rainfall of varying intensities, a relationship was observed between rainfall intensity and K concentration in the runoff.

Another study by Bertol et al. (2003) indicated substantial K losses, irrespective of the management scheme employed. This outcome was attributed to the abundance of K within the soil and its high-water solubility.

Peri et al. (2021) aimed to determine soil erosion rates from the exposed roots of four species of shrubs and dwarf bushes, and they discovered that nitrogen was the primary nutrient lost to erosion, followed by K and P. As part of soil management investigations, Wang et al. (2011) evaluated the impacts of anionic polyacrylamide application and found that its implementation reduced the proportion of K loss through surface runoff. Moreover, in a study on K runoff, Munodawafa et al. (2007) showed that K was more significantly lost under conventional tillage than under mulch ripping and tied ridging practices.

P loss

The models generated for P were similar with SD (Fig. 8), since P has low mobility in soil (Kaufmann et al. 2019). We observed a slight decrease in P loss with increasing Ma. The model of P loss as a function of the dry mass of straw and the green cover showed similar behavior as for K: P loss increased with increasing dry mass of the straw and with decreasing green cover. Modeling P losses is relevant for assessing soil use and management, as P losses in runoff water can increase the risk of eutrophication (Farias et al. 2018; Leite et al. 2018; Wang et al. 2018).

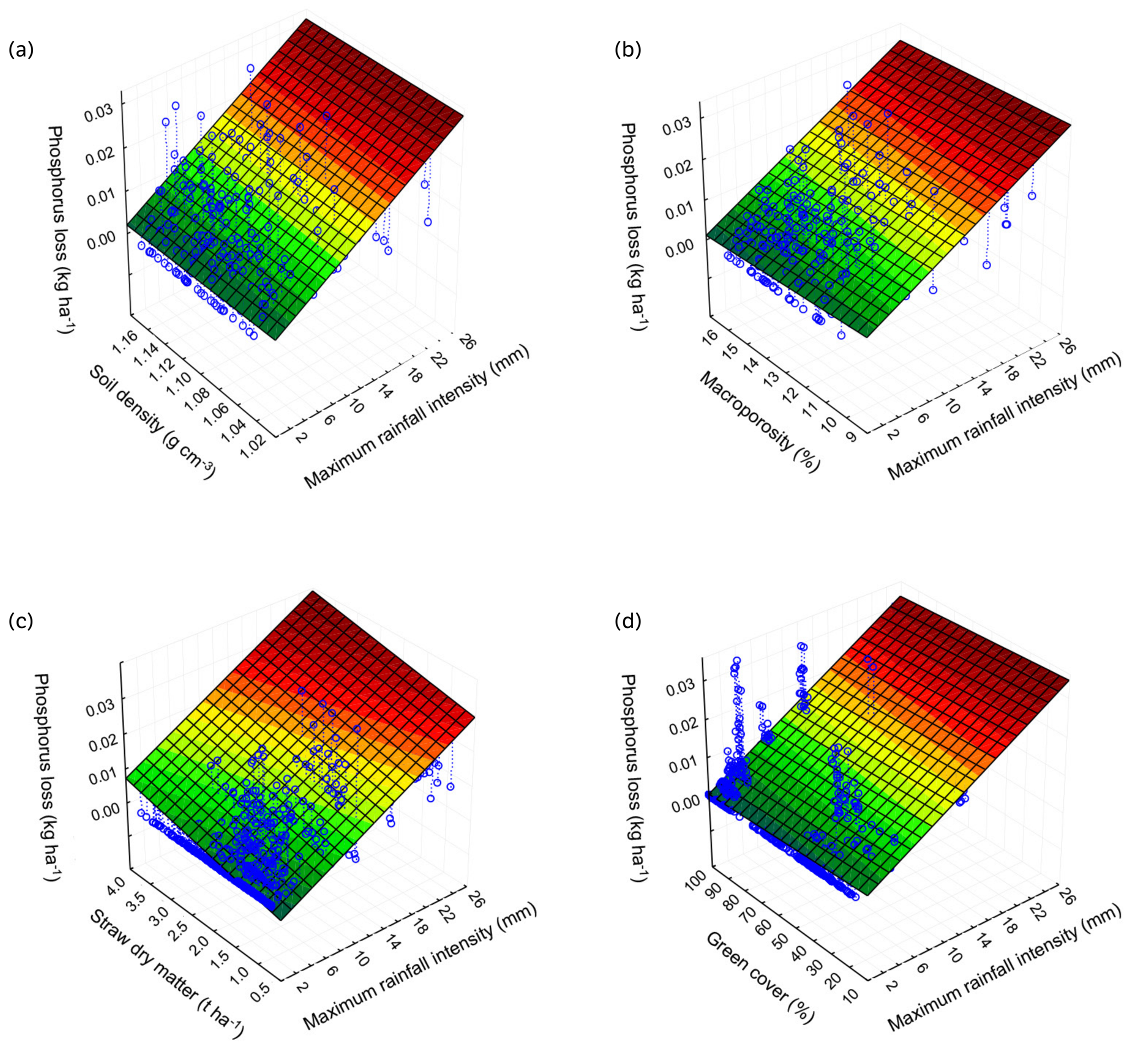

Figure 8. Phosphorus loss affected by (a) soil density, (b) macroporosity, (c) straw dry mass, and (d) green cover.

Bertol et al. (2003) investigated nutrient losses caused by water erosion and found that P concentrations within the runoff were consistently low across all treatments and rainfall sessions applied; a phenomenon potentially attributed to the scanty presence of this element in the soil and its strong colloidal adsorption. To unravel the influence of management systems on the physical quality of a Oxisol, Marques et al. (2010) revealed the sway of management on erosion control, demonstrated by high soil and nutrient losses. Specifically, P and organic matter exhibited pronounced losses in plots subjected to conventional plowing.

Bertol et al. (2010) carried out a study on P loss in a surface runoff generated by simulated rainfall on a Oxisol, regardless of the fertilizer source. This revealed that high-intensity rainfall events resulted in increased concentrations and quantities of P within the runoff. In another study, Bertol et al. (2004) noted that total P losses were more under no-till management practices than under treatments involving scarification with harrowing or plowing with harrowing.

Yang et al. (2023) observed that nutrient transport rates significantly varied across different land uses. Specifically, agricultural lands have lower nutrient transport rates than forested areas. This variation can be attributed to the fact that agricultural lands are predominantly situated on flat terrain (with slopes of less than 2%), which result in minimal soil loss. The precise mechanisms through which dynamic erosion factors contribute to P loss remain unknown (Cheng et al. 2021). Notably, the runoff of P in areas subjected to fertilization is closely associated with the eutrophication of water bodies, suggesting that it has broader environmental implications (Costa et al. 2010).

CONCLUSION

The mathematical model proposed in this study confirmed the hypothesis that soil management strategies can affect soil nutrients. Higher Mg and Ca losses were related to higher SD and lower Ma. Lower Mg, Ca, K, and P losses were associated with lower straw dry mass and higher green cover. K and P losses were stable for all values of SD, but decreased with increasing Ma.

AUTHORS' CONTRIBUTION

Conceptualization: Chang, P. and Secco, D.; **Methodology:** Secco, D., Marins, A. C. and Rizzi, R. L.; **Investigation:** Chang, P.; **Writing – Original Draft:** Chang, P., Bassegio, D. and Savioli, M. R.; **Writing – Review and Editing:** Secco, D., Marins, A. C., Rizzi, R. L. and Bassegio, D. **Supervision:** Secco, D.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study.

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REFERENCES

Adviento-Borbe, M. A. A., Barnes, B. D., Iseyemi, O., Mann, A. M., Reba, M. L., Robertson, W. J., Massey, J. H. and Teague, T. G. (2018). Water quality of surface runoff and lint yield in cotton under furrow irrigation in Northeast Arkansas. Science of the Total Environment, 613-614, 81-87. https://doi.org/10.1016/j.scitotenv.2017.09.020

Bertol, I., Guadagnin, J. C., Cassol, P. C., Amaral, A. D. and Barbosa, F. T. (2004). Perdas de fósforo e potássio por erosão hídrica em um Inceptisol sob chuva natural. Revista Brasileira de Ciência do Solo, 28, 485-494. https://doi.org/10.1590/S0100-06832004000300010

Bertol, I., Luciano, R. V., Bertol, C. and Bagio, B. (2017). Nutrient and organic carbon losses, enrichment rate, and cost of water erosion. Revista Brasileira de Ciência do Solo, 41, e0160150. https://doi.org/10.1590/18069657rbcs20160150

Bertol, I., Mello, E. L., Guadagnin, J. C., Zaparolli, A. L. V. and Carrafa, M. R. (2003). Nutrient losses by water erosion. Scientia Agricola, 60, 581-586. https://doi.org/10.1590/S0103-90162003000300025

Bertol, O. J., Rizzi, N. E., Favaretto, N. and Lana, M. D. C. (2010). Phosphorus loss by surface runoff in no-till system under mineral and organic fertilization. Scientia Agricola, 67, 71-77. https://doi.org/10.1590/S0103-90162010000100010

Bertol, O. J., Rizzi, N. E., Fey, E. and Lana, M. D. C. (2011). Perda de nutrientes via escoamento superficial no sistema plantio direto sob adubação mineral e orgânica. Ciência Rural, 41, 1914-1920. https://doi.org/10.1590/S0103-84782011005000135

Borgmann, C., Secco, D., de Marins, A. C., Zanao Junior, L. A., Bassegio, D., Souza, S. N. M. D. and Silva, T. R. B. D. (2021). Effect of soil compaction and application of lime and gypsum on soil properties and yield of soybean. Communications in Soil Science and Plant Analysis, 52, 1434-1447. https://doi.org/10.1080/00103624.2021.1885688

Bosch, D. D., Potter, T. L., Strickland, T. C. and Hubbard, R. K. (2015). Dissolved nitrogen, chloride, and potassium loss from fields in conventional and conservation tillage. Transactions of the ASABE, 58, 1559-1571. https://doi.org/10.13031/trans.58.11223

Bramorski, J., Trivelin, P. C. O. and Crestana, S. (2015). Nitrogen loss by erosion from mechanically tilled and untilled soil under successive simulated rainfalls. Revista Brasileira de Ciência do Solo, 39, 1204-1211. https://doi.org/10.1590/01000683rbcs20140521

Candido, B. M., Silva, M. L. N., Curi, N. and Batista, P. V. G. (2014). Water erosion post-planting in eucalyptus forests in the Parana river basin, eastern Mato Grosso do Sul, Brazil. Revista Brasileira de Ciência do Solo, 38, 1565-1575. https://doi.org/10.1590/S0100-06832014000500022

Cheng, Y., Li, P., Xu, G., Wang, X., Li, Z., Cheng, S. and Huang, M. (2021). Effects of dynamic factors of erosion on soil nitrogen and phosphorus loss under freeze-thaw conditions. Geoderma, 390, 114972. https://doi.org/10.1016/j.geoderma.2021.114972

[CONAB] Companhia Nacional de Abastecimento (2018). Acompanhamento da safra brasileira de grãos: X levantamento 2017/2018. Brasília: CONAB. Available at: https://www.conab.gov.br/info-agro/safras/graos. Accessed on: Mar. 23, 2023.

Costa, V. L. D., Maria, I. C. D. and Camargo, O. A. D. (2010). Transporte de fósforo pela enxurrada em Latossolo que recebeu lodo de esgoto. Bragantia, 69, 115-123. https://doi.org/10.1590/S0006-87052010000100016

Dechen, S. C. F., Telles, T. S., Guimarães, M. D. F. and Maria, I. C. D. (2015). Losses and costs associated with water erosion according to soil cover rate. Bragantia, 74, 224-233. https://doi.org/10.1590/1678-4499.0363

[EMBRAPA] Empresa Brasileira de Pesquisa Agropecuária (1997). Centro Nacional de Pesquisa de Solos. Manual de Métodos de Análise de Solo. Rio de Janeiro: Embrapa.

Farias, V. L. D. S., Martins Filho, M. V., Paula, D. T. D. and Siqueira, D. S. (2018). Modeling of phosphorus losses by water erosion. Engenharia Agrícola, 38, 149-157. https://doi.org/10.1590/1809-4430-Eng.Agric.v38n1p149-157/2018

Huo, J., Liu, C., Yu, X., Chen, L., Zheng, W., Yang, Y. and Yin, C. (2021). Direct and indirect effects of rainfall and vegetation coverage on runoff, soil loss, and nutrient loss in a semi-humid climate. Hydrological Processes, 35, e13985. https://doi.org/10.1002/hyp.13985

Kaufmann, D. S., Bertol, I., Santos, M. A. D. N. D., Bagio, B., Mecabô, J. and Borg, H. (2019). Impacts of Pig Slurry Applied to Two Different Soils on Nutrient Transport by Runoff. Revista Brasileira de Ciência do Solo, 43. https://doi.org/10.1590/18069657rbcs20180011

Leite, M. H., Couto, E. G., Amorim, R. S. and Scaramuzza, J. F. (2018). Loss of water and nutrients in different soil tillage systems subjected to natural rainfall in the state of Mato Grosso, Brazil. Engenharia Agrícola, 38, 864-873. https://doi.org/10.1590/1809-4430-Eng.Agric.v38n6p864-873/2018

Li, C., Shi, W. and Huang, M. (2023). Effects of Crop Rotation and Topography on Soil Erosion and Nutrient Loss under Natural Rainfall Conditions on the Chinese Loess Plateau. Land, 12, 265. https://doi.org/10.3390/land12020265

Marioti, J., Bertol, I., Ramos, J. C., Werner, R. D. S., Padilha, J. and Bandeira, D. H. (2013). Erosão hídrica em semeadura direta de milho e soja nas direções da pendente e em contorno ao declive, comparada ao solo sem cultivo e descoberto. Revista Brasileira de Ciência do Solo, 37, 1361-1371. https://doi.org/10.1590/S0100-06832013000500025

Marques, S. R., Weill, M. D. A. M. and Silva, L. F. S. D. (2010). Qualidade física de um Latossolo Vermelho, perdas por erosão e desenvolvimento do milho em dois sistemas de manejo. Ciência e Agrotecnologia, 34, 967-974. https://doi.org/10.1590/S1413-70542010000400024

Mendonça, P. G., Silva Júnior, J. F. D., Oliveira, I. R. D., Teixeira, D. D. B., Moitinho, M. R., Martins Filho, M. V., Marques Júnior, J. and Pereira, G. T. (2015). Spatial uncertainty of nutrient loss by erosion in sugarcane harvesting scenarios. Revista Brasileira de Ciência do Solo, 39, 1181-1189. https://doi.org/10.1590/01000683rbcs20140432

Miguel, P., Dalmolin, R. S. D., Pedron, F. D. A., Moura-Bueno, J. M. and Tiecher, T. (2014). Identificação de fontes de produção de sedimentos em uma bacia hidrográfica de encosta. Revista Brasileira de Ciência do Solo, 38, 585-598. https://doi.org/10.1590/S0100-06832014000200023

Munodawafa, A. (2007). Assessing nutrient losses with soil erosion under different tillage systems and their implications on water quality. Physics and Chemistry of the Earth, Parts A/B/C, 32, 1135-1140. https://doi.org/10.1016/j.pce.2007.07.033

Oliveira, L. C. D., Bertol, I., Barbosa, F. T., Campos, M. L. and Mecabô Junior, J. (2015). Perdas de solo, água e nutrientes por erosão hídrica em uma estrada florestal na Serra Catarinense. Ciência Florestal, 25, 655-665. https://doi.org/10.5902/1980509819616

Ouyang, W., Wu, Y., Hao, Z., Zhang, Q., Bu, Q. and Gao, X. (2018). Combined impacts of land use and soil property changes on soil erosion in a mollisol area under long-term agricultural development. Science of The Total Environment, 613-614, 798-809. https://doi.org/10.1016/j.scitotenv.2017.09.173

Pandey, A., Himanshu, S. K., Mishra, S. K. and Singh, V. P. (2016). Physically based soil erosion and sediment yield models revisited. Catena, 147, 595-620. https://doi.org/10.1016/j.catena.2016.08.002

Patrignani, A. and Ochsner, T. E. (2015). Canopeo: A powerful new tool for measuring fractional green canopy cover. Agronomy Journal, 107, 2312-2320. https://doi.org/10.2134/agronj15.0150

Peri, P. L., Lasagno, R. G., Chartier, M. P., Roig Junent, F. A., Rosas, Y. M. and Martínez Pastur, G. J. (2021). Soil erosion rates and nutrient loss in rangelands of Southern Patagonia. Imperiled: the Encyclopedia of Conservation, 102-110. https://doi.org/10.1016/B978-0-12-821139-7.00183-5

R Core Team (2019). R: A Language and Environment for Statistical Computing. Vienna: R Development Core Team.

Reinert, D. J. and Reichert, J. M. (2006). Coluna de areia para medir a retenção de água no solo: protótipos e teste. Ciência Rural 36, 1931-1935. https://doi.org/10.1590/S0103-84782006000600044

Soil Survey Staff (2014). Keys to soil taxonomy. 12th ed. Washington, D.C.: USDA.

Statsoft, Inc (2011). Statistica (data analysis software system), version 10. Statsoft, Inc.

Wang, A-P., Li, F.-H. and Yang, S.-M. (2011). Effect of polyacrylamide application on runoff, erosion, and soil nutrient loss under simulated rainfall. Pedosphere, 21, 628-638. https://doi.org/10.1016/S1002-0160(11)60165-3

Wang, W., Wu, X., Yin, C. and Xie, X. (2019). Nutrition loss through surface runoff from slope lands and its implications for agricultural management. Agricultural Water Management, 212, 226-231. https://doi.org/10.1016/j.agwat.2018.09.007

Wang, Z., Zhang, T. Q., Tan, C. S., Taylor, R. A. J., Wang, X., Qi, Z. M. and Welacky, T. (2018). Simulating crop yield, surface runoff, tile drainage and phosphorus loss in a clay loam soil of the Lake Erie region using EPIC. Agricultural Water Management, 204, 212-221. https://doi.org/10.1016/j.agwat.2018.04.021

Yang, X., Leys, J., Zhang, M. and Gray, J. M. (2023). Estimating nutrient transport associated with water and wind erosion across New South Wales, Australia. Geoderma, 430, 116345. https://doi.org/10.1016/j.geoderma.2023.116345