Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 119 No. 1 (2018) 23–35

urn:nbn:de:hebis:34-2018010454110 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Applying phosphorus indices at a small agricultural watershed in Southern Brazil

Josiane C. N. Waltrick[a], Gabriel D. Goularte[b], Nerilde Favaretto[b,*], Luiz C. P. Souza[b], Jeferson Dieckow[b], Volnei Pauletti[b], Fabiane M. Vezzani[b], Luciano Almeida[c], Jean P. G. Minella[d]

[a]*Department of Education of Paraná State, Av. Água Verde, 2140, Vila Izabel, CEP 80240-900, Curitiba, Paraná, Brazil*

[b]*Department of Soil Science and Agricultural Engineering, Federal University of Paraná,*
Rua dos Funcionários 1540, CEP 80035-050, Curitiba, Paraná, Brazil

[c]*Department of Agricultural Economics and Extension, Federal University of Paraná,*
Rua dos Funcionários 1540, CEP 80035-050, Curitiba, Paraná, Brazil

[d]*Department of Soil Science, Federal University of Santa Maria, Av. Camobi, 1000, CEP 97105-900, Santa Maria, Rio Grande do Sul, Brazil*

Abstract

Best management practices at watershed scale are essential to mitigate water pollution. The objectives of this study were: (1) to estimate the P-index in a small watershed with intensive agricultural use applying five P-index versions at three scales (watershed, sub-basin and agricultural field); (2) to assess the effect of the connectivity factors (distance between the agricultural field and the stream and width of riparian native vegetation) in estimating the risk of P loss. The five P-index versions resulted in a similar risk of P loss, 75 to 83 % of the whole watershed scale (agricultural plus forest areas) was classified as low or very low risk for P loss. At the agricultural area scale, 79 to 100 % of this area was classed as high and very high risk for P loss. The low risk of P loss at watershed scale is explained by the high occurrence of forest vegetation. The reduced distance between agricultural land and streams and/or the reduced width of riparian native vegetation increased the risk of P loss. Estimated P-index values at a sub-basin scale indicated lower risk of P loss compared to agricultural field scale. In order to better estimate the risk of P loss at an agricultural field scale, we advise using a P-index which considers also connectivity factors.

Keywords: P-index, P risk assessment, water quality, catchment, riparian vegetation, runoff

1 Introduction

Phosphorus (P) is an essential nutrient for plants, and extensively applied on agricultural fields. However, in an aquatic environment P is associated with eutrophication (Correll, 1998; Daniel *et al.*, 1998; Schindler *et al.*, 2008) causing detrimental impacts on aquatic life and derived products for human use (Kay *et al.*, 2009). It is transferred from agricultural fields into streams mainly via surface runoff due to its low mobility in soil (Leinweber *et al.*, 2002; Sharpley & Wang, 2014). Soil P content plays an important role in water pollution, given that high soil P increases the potential for P loss by surface runoff (Pote *et al.*, 1999). To ensure high productivity, ever-growing amounts of organic and inorganic fertilisers have been added to soils in intensive agricultural systems (Hooda *et al.*, 2000; Kleinman *et al.*, 2002). So, especially sloped areas associated with P over-fertilisation become high risk sites of P transport from soil to water (Shigaki *et al.*, 2006; Sharpley *et al.*, 2001; Gburek *et al.*, 2000).

To assess P losses from agricultural land into surface water the P-index was developed as a semiquantitative tool (Sharpley *et al.*, 2001). This would aid farmers to decide about which practices should be applied in soil man-

---

* Corresponding author
Nerilde Favaretto (nfavaretto@ufpr.br)
Phone: 55-41-33505638

agement and P fertilisation, considering both agronomic (plant production) and environmental (water quality) aspects (Sharpley *et al.*, 2003; Buczko & Kuchenbuch, 2007).

The P-index is a simple combination of several factors related to P transport and P source. Most versions of P-index consider soil erosion and surface runoff as transport factors, and soil content, amount and method of P application as source factors. Differences among versions are related to factor weight, and variables such as connectivity, presence of animals, and critical areas (Buczko & Kuchenbuch, 2007). Connectivity between fields and receiving water i.e. distance from field to the stream and width of riparian buffer zone, have been included in several P-index versions (Sharpley *et al.*, 2003). Another difference among P indices is the way to calculate the P-index score. Originally published by Lemunyon & Gilbert (1993), the P-index was additive (P-index scores the sum of factors). Later versions were modified utilising a multiplicative approach, where P-index score is calculated by multiplying the transport factor by the source factor. In all versions, the final P-index score is ranked on a scale from very low to excessive, indicating the risk of water contamination by P (Sharpley *et al.*, 2003; Buczko & Kuchenbuch, 2007). In the U.S.A. for example, there are 47 different versions to estimate the P-index (Sharpley *et al.*, 2003). Canada (Reid, 2011) and several European countries (Heathwaite *et al.*, 2003; Bechmann *et al.*, 2005) also developed variations of the P-index. In Brazil, some studies have been done with P indices from other countries (Lopes *et al.*, 2007; Oliveira *et al.*, 2010). Recently, Couto *et al.* (2015) applied two versions of the P-index (modified from Lemunyon & Gilbert, 1993 and Flynn *et al.*, 2000), to evaluate P loss from agricultural land after long-term application of pig slurry in Southern Brazil. However, so far, there is no Brazilian P-index.

P indices are empirical and developed using the best available professional knowledge from a wide range of scientific literature (Sharpley *et al.*, 2003). Therefore, it is not possible to calibrate the P-index as a mathematical model; however, it is possible and very important to evaluate the sensitivity of this framework using measured data (Buczko & Kuchenbuch, 2007). This sensitive evaluation allows to asses if the framework is correlated with P losses and also to identify which component has the greatest influence on the P-index scores. Several studies comparing estimated and measured values have been conducted at small and large field plots as well as at watershed (Sharpley, 1995; Gburek *et al.*, 2000; Eghball & Gilley, 2001; Veith *et al.*, 2005; Bechmann *et al.*, 2007).

The objectives of this study were: (1) to estimate the P-index in a small watershed with intensive agricultural use (Colombo, Paraná, Brazil) applying five P-index versions obtained by an additive approach at three scales (watershed, sub-basin and agricultural field); (2) to assess the effect of the connectivity factors (distance between the agriculture field and the stream and width of riparian native vegetation) in estimating the risk of P loss.

The Campestre watershed was chosen for this study because it is characterised by intensive vegetable farming using high rates of mineral and organic fertilisers, as well as the presence of shallow soils and sharp slopes. Moreover, almost 50 % of the riparian zone (30 m at each side of the river) is not covered by native vegetation (Ribeiro *et al.*, 2014). In this scenario, a high risk of phosphorus loss from agricultural areas was expected.

2 Materials and methods

2.1 Site description

The study area (1010 ha) was the Campestre watershed, Colombo, northern metropolitan region of Curitiba, Paraná, Brazil (Fig. 1). The climate is classified as Cfb (mesothermal humid subtropical) by Koeppen with cool summers and no dry season. The average of minimum and maximum temperature is 12 and 22 ºC, respectively. The average annual rainfall over of the last 22 years amounted 1479 mm (Caviglione *et al.*, 2000).

The slope was determined using topographic data (1 : 10 000 scale, with contour lines every 5 m in digital media). Agriculture occurred predominantly in areas with steep slopes (70 % of agriculture occurred with slope $> 13\,\%$) (Table 1). The predominant slope was 20–45 % followed by 13–20 % (representing 45 % and 24 % of the watershed, respectively).

Land cover and soil use was obtained from an aerial photography at a scale of 1 : 30 000 (Suderhsa, 2000) and revised by field survey (Ribeiro *et al.*, 2014), describe as follow: (a) 44 % was covered by native vegetation, predominantly characterised by secondary forest at different stages of regeneration; (b) 23 % was covered with reforested wood species such as *Mimosa scabrella* Benth. and *Eucalyptus* spec.; (c) 19 % was used for agriculture predominantly for vegetable production including lettuce (*Lactuca sativa* L.), broccoli (*Brassica oleracea* var. *italica* L.), cauliflower (*Brassica oleracea* var. *botrytis* L.), squash (*Cucurbita pepo* L.), beetroot (*Beta vulgaris* L.), swiss chard (*Beta vulgaris* L.), cucumber (*Cucumis sativus* L.), tomato (*Lycopersicon esculentum* Mill.), pepper (*Capsicum annuum* L.), green beans (*Phaseolus vulgaris* L.); and (d) 14 % was used as animal pasture or unused.

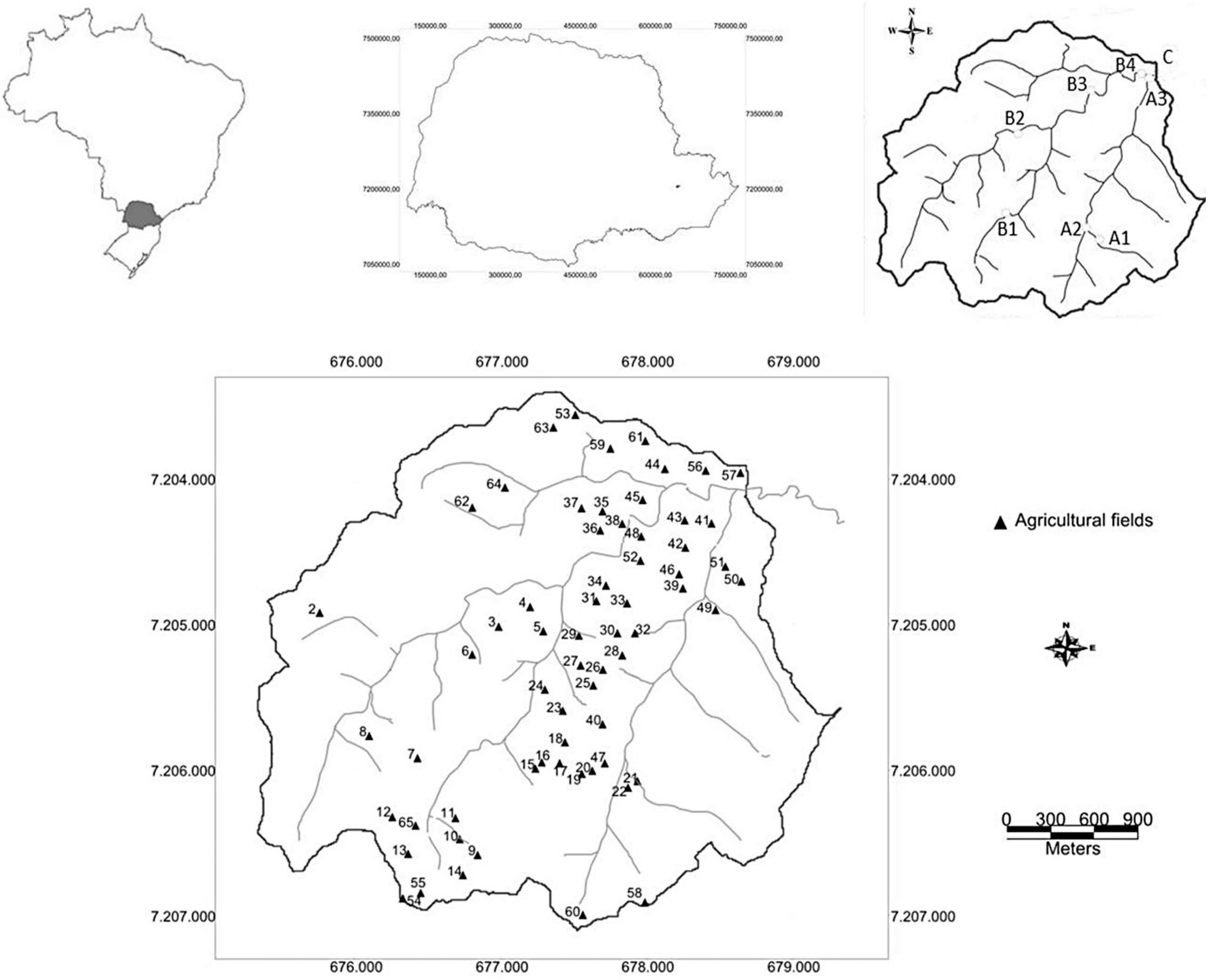

Fig. 1: *Localisation of the Campestre watershed, the sub-basins and the agricultural fields, Colombo, Paraná, Brazil.*

The soil management was based on conventional tillage (ploughing and harrowing predominantly with animal traction) with heavy use of mineral and organic fertilisers (poultry litter). However, some farmers practiced a conservation tillage based on the organic production.

Further information on Campestre watershed characterisation can be found in Ribeiro *et al.* (2014) and Ramos *et al.* (2014).

The soil survey was performed on 14 soil profiles coming from different landscape positions (summit, shoulder, backslope and footslope) based on Embrapa (2006). There were 11 soil units (loam and clay loam texture) distributed among Cambisol (50 %), Association of Cambisol and Leptosol (42 %), Leptosol (4 %), Ferralsol (3 %) and Gleysol (1 %) (FAO-World Reference Base for Soil Resources). Further information on soil classification of the watershed can be found in Ribeiro *et al.* (2014).

2.2 *Versions of P-index*

As no Brazilian P-index exists, five different versions from the U.S.A. were applied (Original – Lemunyon & Gilbert, 1993; New Mexico – Flynn *et al.*, 2000; Alabama – NRCS, 2001; Nebraska – Eghball & Gilley, 2001; Montana – Fasching, 2006). These five versions were chosen because they all used an additive framework, which means the final P-index is calculated from the sum of the site characteristics (factors). P-index with multiplicative frameworks were not chosen to facilitate the comparison using only additive framework. Table 2 describes the framework of the original version (Lemunyon & Gilbert, 1993) and Table 3 describes the contribution of each factor in the five different versions of P-index used in our study. The original and Nebraska versions consider the same factors (erosion and surface runoff as transport factors; soil P, rate and application method of mineral and organic fertilisers as source factors) but with different weights. The Alabama, Montana and New Mexico versions have all these factors plus the connectivity factors

Table 1: *Land use (ha) in each slope class in the Campestre watershed, Colombo, Paraná, Brazil.*

Sub-basin	*Land use*	*Slope (%)*							$\sum$
		0–3	> 3–8	> 8–13	> 13–20	> 20–45	> 45–75	> 75	
A1	Agriculture	0	0	0	0	0	0	0	0
	Whole	0	0.2	0.8	4.3	20.2	7.3	2.7	35
A2	Agriculture	0.1	0.6	2.9	2.0	2.9	0.2	0.0	8
	Whole	0.2	2.4	12.3	25.1	69.2	19.7	5.8	134
A3 (A1+A2)	Agriculture	0.1	1.1	7.7	7.6	10.6	1.3	0.2	28
	Whole	0.5	6.6	36.3	68.2	164.3	43.1	12.1	331
B1	Agriculture	0.1	4.2	7.4	10.5	8.8	0.9	0.1	32
	Whole	0.7	17.0	20.4	27.8	28.8	4.2	0.9	99
B2	Agriculture	0.1	1.3	3.4	4.2	3.5	0.3	0.0	13
	Whole	0.8	10.0	36.3	59.9	123.0	30.2	6.8	267
B3	Agriculture	0.5	9.9	25.2	39.6	39.7	3.1	0.5	118
	Whole	2.2	35	81.5	133.0	211.6	41.9	9.8	515
B4 (B1+B2+B3)	Agriculture	0.5	14.0	32.2	51.0	58.0	5.8	1.3	163
	Whole	2.5	44.0	104	170	284.4	56.6	14.1	675
C (A3 + B4)	Agriculture	0.6	15.0	40.4	58.9	68.8	7.2	1.6	192
	Whole	3	50	141	240	450	100	26	1010

Table 2: *Framework of the original P-index (after Lemunyon & Gilbert, 1993).*

Site characteristics (factors)	*Weight*	*Phosphorus loss rating (value)*				
		None (0)	Low (1)	Medium (2)	High (4)	Very High (8)
Transport factors:						
1. Soil erosion $(\mathrm{t\,ha^{-1}\,year^{-1}})$[†]	1.5	Not applicable	< 12	12–25	25–37	> 37
2. Runoff class	0.5	Negligible	Very Low or Low	Medium	High	Very High
Source factors:						
1. Soil P test	1.0	Not applicable	Low	Medium	High	Very High
2. P fertiliser (mineral) application rate $(\mathrm{kg\,ha^{-1}\,year^{-1}\,P_2O_5})$[‡]	0.75	None applied	1–34	35–100	101–168	> 168
3. P fertiliser (mineral) application method	0.5	None applied	Placed with planter deeper than 5 cm[§]	Incorporated immediately before crop	Incorporated > 3 months before crop or surface applied < 3 months before crop	Surface applied > 3 months before crop
4. P fertiliser (organic) application rate $(\mathrm{kg\,ha^{-1}\,year^{-1}\,P_2O_5})$[‡]	1.0	None applied	1–34	35–67	68–100	> 100
5. P fertiliser (organic) application method	1.0	None applied	Injected deeper than 5 cm[§]	Incorporated imediatley before crop	Incorporated > 3 months before crop or surface applied < 3 months before crop	Surface applied to pasture or > 3 months before crop

[†] Unit transformed from t ac^{-1} to t ha^{-1}; [‡] Unit transformed from lbs ac^{-1} to kg ha^{-1}; [§] Unit transformed from inches (in.) to centimetres (cm).
Final P-index = $\sum$ (factor $*$ weight).

Table 3: *Contribution of each factor in the five versions of P-index used in our study*[†].

Site characteristics (factors)	*Original*		*Nebraska*		*Alabama*				*Montana*				*New Mexico*			
					in		*out*		*in*		*out*		*in*		*out*	
	Weight	(%)	Weight	(%)	Weight	(%)	Weight	(%)	Weight	(%)	Weight	(%)	Weight	(%)	Weight	(%)
Transport factors:																
1. Soil erosion	1.5	24	4.0	50	3.0	16	3.0	21	1.5	19	1.5	21.4	1.5	15	1.5	21.4
2. Runoff class	0.5	8	0.5	6	4.0	21	4.0	30	0.5	6	0.5	7.1	1.5	15	1.5	21.4
Source factors:																
1. Soil P test	1.0	16	0.5	6	1.0	5	1.0	7	1.0	12.5	1.0	14.3	1.0	10	1.0	14.3
2. P fertiliser (mineral or mineral + organic) application rate	0.75	12	0.5	6	3.0	16	3.0	21	1.0	12.5	1.0	14.3	1.0	10	1.0	14.3
3. P fertiliser (mineral or mineral + organic) application method	0.5	8	1.0	13	3.0	16	3.0	21	1.0	12.5	1.0	14.3	1.0	10	1.0	14.3
4. P fertiliser (organic) application rate	1.0	16	0.5	6					1.0	12.5	1.0	14.3				
5. P fertiliser (organic) application method	1.0	16	1.0	13					1.0	12.5	1.0	14.3	1.0	10	1.0	14.3
Connectivity factors:																
1. Distance between agricultural field and streams					3.0	16			1.0	12.5			1.5	15		
2. Riparian filter strip width					2.0	10							1.5	15		

[†] *in* = with connectivity factors; *out* = without connectivity factors.

Table 4: *Interpretation of risk of P loss for the different P-index versions.*

Risk of P loss	*Original* (Lemunyon & Gilbert, 1993)	*Nebraska* (Eghball & Gilley, 2001)	*Alabama* (NRCS, 2001)	*Montana* (Fasching, 2006)	*New Mexico* (Flynn *et al.*, 2000)
Very low					0–10
Low	< 8	< 3	< 65	< 11	11–17
Medium	8–14	3–6.5	66–75	11–21	18–27
High	15–32	6.6–10	76–85	22–43	28–37
Very high	> 32	> 10	86–95	> 43	38–47
Extremely high			> 95		> 47

(distance between agricultural field and the stream and/or width of the filter strip) in its framework. The final P-index score indicates the relative vulnerability to P loss from a field following each version (Table 4).

The P-index was applied at three scales: watershed (C); sub-basin (seven sub-basins: A1, A2, A3, B1, B2, B3 and B4) (Fig. 1 and Table 1) and field (65 agricultural fields) (Fig. 1). The agricultural fields represented all hillslopes with vegetables production existent in the watershed.

The similarity of P-index at sub-basin and agricultural fields was analysed by the Euclidian distance and the cluster analysis was applied using the MATLAB software (MathWorks, 2017).

2.3 Estimation of P-index

The P-index was estimated using IDRISI 15.0 software (Eastman, 1999). In the following, the estimation of the source, transport and connectivity factors used for the calculation of the P-index is briefly described. More detailed information on these factors can be found in Waltrick (2011).

2.3.1 Estimation of source factors

(a) Soil P content: Soil samples (73 samples composed of 20 sub-samples) were taken at a depth of 0–20 cm on 65 agricultural fields, three representative grassland fields and five representative forest fields. The samples were air dried,

homogenized and passed through a 2 mm mesh. The P Mehlich I (the standard soil test for farmers in Paraná State) was determined according to Sparks (1996) and Pavan *et al.* (1992). The soil P status (low, medium, high, very high) was classified following the recommendation for Paraná state (SBCS, 2004).

(b) Amount and method of organic and mineral P application: Information was obtained through interviews with the farmers of all agricultural fields. Cauliflower and Swiss chard were regarded as the main crops as these were most prevalent and received the larger quantity of mineral and organic fertilisers.

2.3.2 Estimation of transport factors

(a) Erosion: The risk of soil loss was not available from any national source. Therefore, soil loss was estimated using the Revised Universal Soil Loss Equation ($A = R\,K\,LS\,C\,P$) (Renard *et al.*, 1997) with IDRISI 15.0 software (Eastman, 1999). Rainfall erosivity (R) was calculated according to Rufino *et al.* (1993), using a historic series from 1988 to 2009. Soil erodibility (K) was calculated according to Roloff & Denardin (1994). Slope (LS) was calculated according to Moore & Burch (1986) and Engel & Mohtar (2006). Input data on cover management (C) and conservation practices (P) was obtained from Bertoni & Lombardi Neto (1999).

(b) Surface runoff: Surface runoff (water loss) was estimated according to soil permeability and slope based on Fasching (2006). Permeability was determined in the field for each soil class as reported by Santos *et al.* (2005) while slope was defined using the SPRING 15.0 software with topographic data in digital media (1 : 10 000 scale, with contour lines every 5 m).

2.3.3 Estimation of connectivity factors

Riparian filter strip width and distance between agricultural land and the watercourse (in meters) was determined using the IDRISI 15.0 software (Eastman, 1999).

3 Results

3.1 Evaluation of source, transport and connectivity factors

The average soil P Mehlich I in 0-20 cm was 2.5 mg dm^{-3} in the forest vegetation areas ($n = 3$), 2.7 mg dm^{-3} in the grassland ($n = 5$) and 120.7 mg dm^{-3} in the agriculture fields ($n = 65$; varying from 9.1 to 325.2 mg dm^{-3} P). In loam and clay loam texture, soil P Mehlich I above 24.0 mg dm^{-3} is classified as very high in Paraná state (SBCS, 2004). According to all five P-index estimation versions most results of the soil P analyses for agricultural land in the Campestre watershed were classified as very high risk of P loss (data not shown). The high soil P content is due to the large quantities of P being applied as fertilisers to crops in the summer and winter seasons. An estimated 48 Mg ha^{-1} year^{-1} of poultry litter was applied, a total of 1.152 kg P_2O_5 ha^{-1} year^{-1} (503 kg P ha^{-1} year^{-1}) of organic fertilization. In the conventional system, farmers applied organic fertiliser (48 Mg ha^{-1} year^{-1}) plus 4 Mg ha^{-1} year^{-1} of mineral fertiliser (10-10-10), 400 kg P_2O_5 ha^{-1} year^{-1} (175 kg P ha^{-1} year^{-1}) of mineral fertilization (Ribeiro *et al.*, 2014). 120 to 450 kg of P_2O_5 ha^{-1} depending on soil P content are the amounts recommended for most vegetable crops in Paraná State (SBCS, 2004). The application of organic and mineral fertilisers occurs immediately before manual planting, which gives a medium risk of P loss in all P-index versions.

The highest estimated soil loss occurred on cultivated land. Out of the 192 ha used for agriculture (Table 1), 175 ha showed soil losses of above 37 t ha^{-1} year^{-1}. This rate is classified as very high risk of P loss in all five P-index versions. Surface runoff was classified as high on more than 52 % of the total watershed. High runoff associated with high soil loss indicates an increased risk of P loss, especially on the cultivated fields.

According to Brazilian law (Brasil, 2012), 30 m on each side of a stream should be preserved with native vegetation as riparian buffer. For the Campestre watershed, using the buffer routine from IDRISI 15.0, this would mean 135 ha of riparian zone, however, only 57 % of this riparian zone was covered with native forest (Fig. 2). Sub-basin A was the most protected by riparian vegetation: 60.1 % was covered by native forest, 22.3 % was covered with reforested wood species, 11.2 % was used as animal pasture or fallow land and only 6.4 % was agricultural area. On the other hand 19 % of the riparian zone in sub-basin B was agricultural area. Also, most agricultural production occurred very near or inside the riparian zone (Fig. 2). Of the 192 ha under cultivation, 20 ha were located inside the riparian zone and only 50 ha were more than 300 m away from a watercourse.

3.2 P-index at watershed, sub-basin and agricultural field scale

The five P-index versions resulted in a similar risk of P loss, 75 % to 83 % of the whole watershed was classified as low or very low risk of P loss. Additionally, while analysing the P-index for the agricultural area, it was noted that 79 to 100 % of this area was classed as high and very high risk of P loss (Table 5). Exemplarily, Fig. 3 illustrates the results of the original P-index (Lemunyon & Gilbert, 1993).

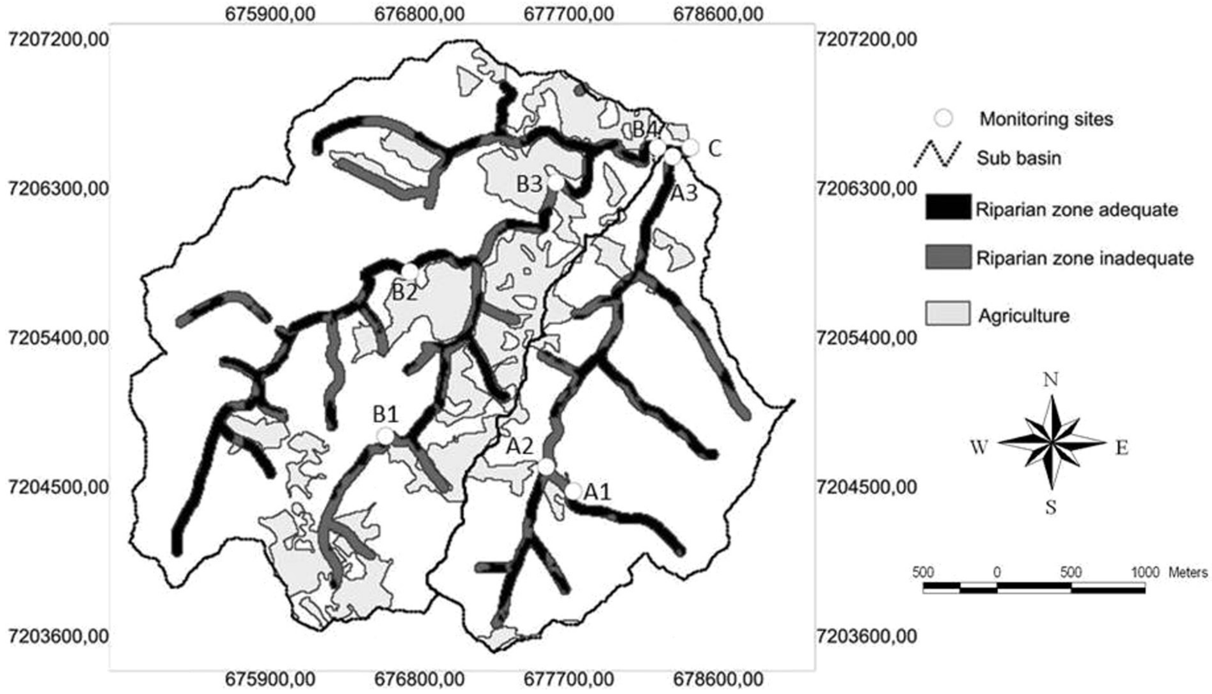

Fig. 2: *Agricultural area and riparian zone in the Campestre watershed, Colombo, Paraná, Brazil.*

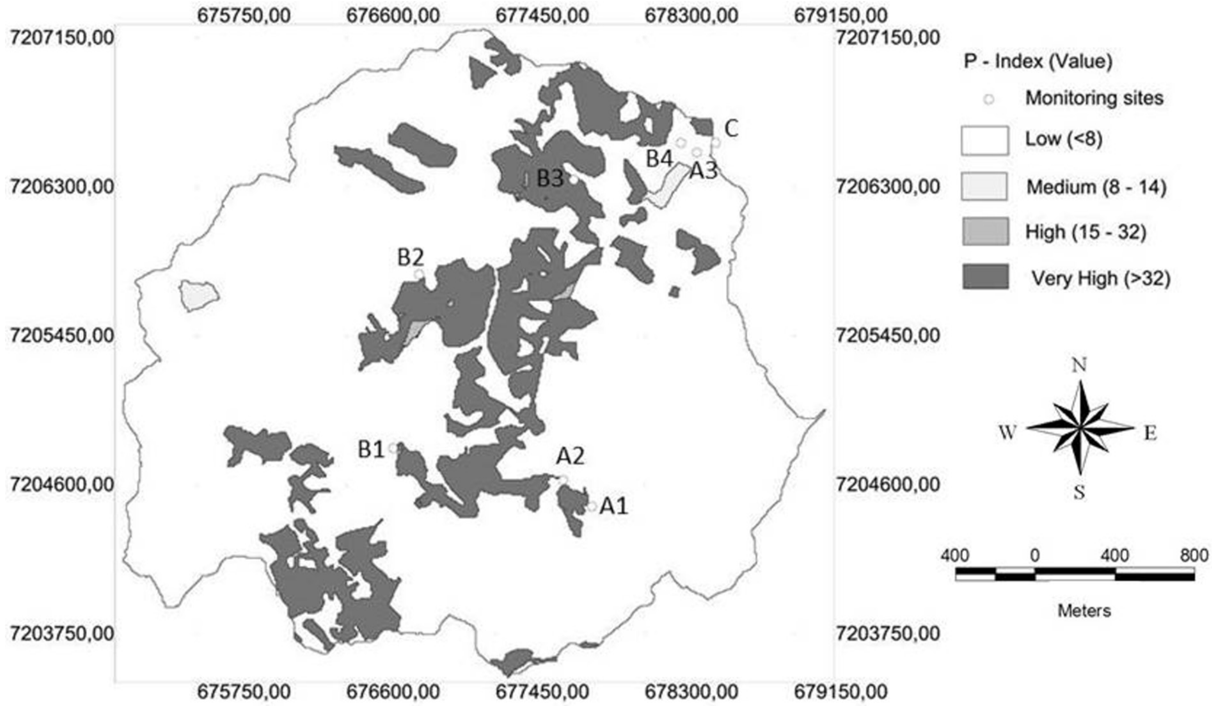

Fig. 3: *P-index estimation based on Lemunyon & Gilbert (1993) for the different sub-basins of the Campestre watershed, Colombo, Paraná, Brazil.*

Table 5: *Estimation of the risk of P loss using different P-index versions for the whole watershed (Whole) and for the agricultural area (Agric.) in the Campestre watershed, Colombo, Paraná, Brazil*[†].

Risk of P loss (P-index class)	*% of the P-index class*									
	Original (Lemunyon & Gilbert, 1993)		*Nebraska* (Eghball & Gilley, 2001)		*Alabama* (NRCS, 2001)		*Montana* (Fasching, 2006)		*New Mexico* (Flynn *et al.*, 2000)	
	Whole	Agric.	Whole	Agric.	Whole	Agric.	Whole	Agric.	Whole	Agric.
Very Low									80.9	
Low	80.9	–	74.5	0.3	82.5	5.5			0.1	–
Medium	0.1	0.1	7.0	3.1	2.9	15.6	80.9	–	0.5	1.6
High	2.6	11.7	0.6	0.3	3.1	16.8	0.5	–	2.4	13.1
Very High	16.4	88.2	17.9	96.3	1.0	5.5	0.2	1.2	4.8	24.7
Extremely High					10.5	56.5	18.4	98.8	11.3	60.6

[†] Alabama, Montana and New Mexico P-index with connectivity factors.

Table 6: *Estimated P-index (mean value) at sub-basin scale (whole sub-basin (Whole) and for the agricultural area (Agric.) in the Campestre watershed, Colombo, Paraná, Brazil*[†].

Sub-basin	*Original* (Lemunyon & Gilbert, 1993)		*Nebraska* (Eghball & Gilley, 2001)		*Alabama* (NRCS, 2001)		*Montana* (Fasching, 2006)		*New Mexico* (Flynn *et al.*, 2000)	
	Whole	Agric.	Whole	Agric.	Whole	Agric.	Whole	Agric.	Whole	Agric.
A1	4	–	2	–	11	–	5	–	5	–
A2	6	29	2	13	16	85	9	56	8	46
A3	6	39	2	13	16	86	8	57	8	46
B1	15	29	5	13	38	99	21	58	20	53
B2	5	39	2	13	15	96	7	56	8	52
B3	12	30	4	13	30	95	16	57	16	52
B4	12	31	4	13	30	94	17	57	16	51
C (A+B)	11	39	3	13	25	93	14	57	14	50

[†] Alabama, Montana and New Mexico P-index with connectivity factors.

At a sub-basin scale, there was a greater risk of P loss in sub-basin B than in sub-basin A (Table 6).

We compared the mean P-index across seven sub-basins and between 65 agricultural plots. We observed a greater value as well as a greater variation in P loss risk across fields than at the sub-basin scale. For example, the result (mean value) of the original P-index at sub-basin scale (whole area of the sub-basin) varied from 4 to 15 and at agricultural fields varied from 29 to 39 (Table 6). For the 65 agricultural fields, the minimum P-index was 14 and the maximum was 40 (data not shown). Bechmann *et al.* (2007), testing the Norwegian P-index across 50 fields and 9 sub-basins also observed a greater difference in risk of P loss at the field scale.

The Euclidian distance and cluster analysis showed the difference of scales between the cluster “agricultural fields” and the cluster “sub-basins” (Fig. 4a).

3.3 *Effect of the connectivity factors*

Connectivity factors such as distance between cropped fields and water streams, which effectively means the distance between P application and water course and/or riparian filter strip width are included in most P-index versions (Sharpley *et al.*, 2003; Buczko and Kuchenbuch, 2007). From the five versions applied in this study, three of these included the connectivity factor in their frameworks (Table 3). According to the New Mexico P-index version (Flynn *et al.*, 2000), the risk of P loss is very low with riparian buffer > 30 m. The Alabama P-index (NRCS, 2001) is less restrictive; the risk of P loss is classified as very

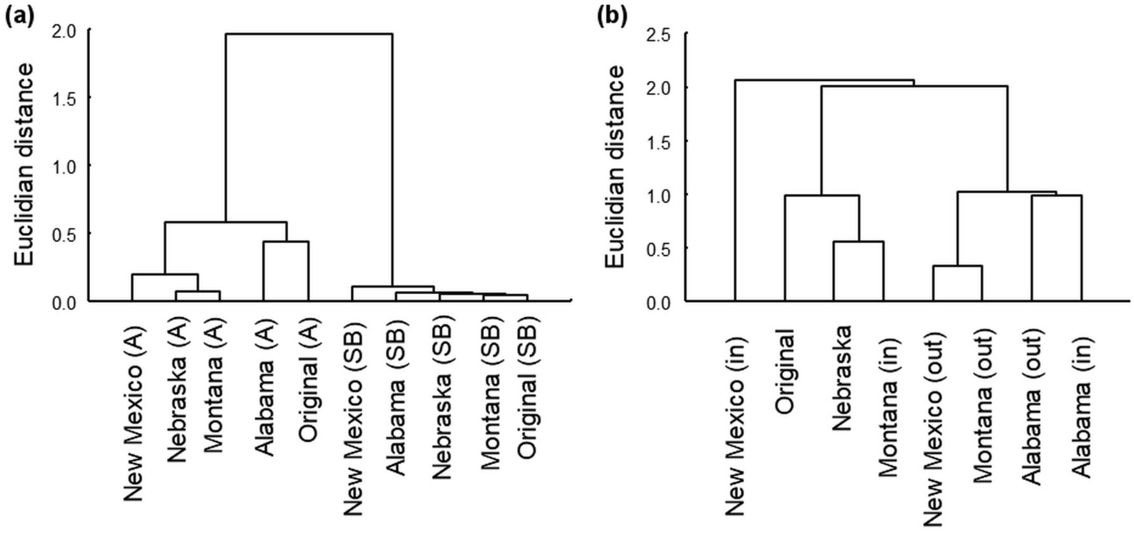

Fig. 4: *Dendrogram of the P-index versions in the Campestre watershed, Colombo, Paraná, Brazil:* ***(a)*** *agricultural fields (A) and sub-basins (SB);* ***(b)*** *agricultural fields with (*in*) and without (*out*) the connectivity factors.*

low with riparian buffer >15 m. According to the Montana P-index (Fasching, 2006), the risk of P loss and distance between watercourse and agriculture was: < 30 m, very high and > 600 m, very low. The New Mexico (Flynn *et al.*, 2000) is less restrictive (very low risk of P loss with distance from the agriculture field to the stream > 300 m and very high risk with distance < 9 m). The Alabama (NRCS, 2001) also is less restrictive (very low risk of P loss with distance from the agriculture field to the stream > 122 m and very high risk with distance < 5 m).

The mean P-index calculated for a whole watershed in the Alabama version varied from 24 to 25 (without and with the connectivity factors, respectively), remaining in the same risk of P loss (low). However, the mean P-index of agricultural area varied from 84 to 93 (without and with the connectivity factors, respectively), increasing the risk of P loss from high to very high (Table 7).

Taking into account the distance between cropped fields and water streams in the Montana version, the P-index values for the agricultural area were also modified (Table 7). In this version, without considering the connectivity factor, the average P-index was 27 (high risk of P loss). However, when this factor was considered, the average P-index increased to 57 (very high risk of P loss).

In the New Mexico version, there was an increase in the estimated P-index value with the connectivity factors. The average P-index across the whole watershed increased from 10 to 14 and for agricultural area from 35 to 50 (Table 7), modifying the risk from high to extremely high.

3.4 P indices at agricultural field scale

The cluster analysis identified the similarity among the P-index versions tested at agricultural field scale (Fig. 4b). In general, the versions Alabama (*in* and *out*), Montana (*out*) and New Mexico (*out*) formed a well-defined cluster (Fig. 4b) with 23 to 62 % of agricultural fields classified as very high and extremely high risk of P loss (Fig. 5). The Original, Nebraska, and Montana (*in*) formed the second cluster with 88 to 99 %, and New Mexico (*in*) individually formed a third cluster (Fig. 4b) with 85 % within the very high and extremely high risk of P loss category (Fig. 5). The Montana and New Mexico versions were sensitive to the connectivity factors (Fig. 4b). When the distance between agriculture field and the stream and/or the riparian filter strip were considered, the classification of very high and extremely high risk of P loss decreased from 99 to 49 % for the Montana version and from 85 to 23 % for the New Mexico version (Fig. 5). The Alabama version also decreased the proportion of areas classified as very high and extremely high risk of P loss when the connectivity factor was included (Fig. 5), however, the cluster analysis identified still similarities between both cases (Fig. 4b). The Original and Nebraska versions do not consider connectivity factors in their frameworks, but these versions also showed high percentage of areas classified as very high and extremely high risk of P loss. These results are explained by the soil erosion factor weighting 24 and 50 %, respectively (Table 3). Even without considering the distance between agriculture field and the stream and the riparian filter strip, 92 % (on average) of the agricultural fields was classified as very high and extremely high risk of P loss (Fig. 5).

Table 7: *P-index (mean value and risk) at whole watershed and at agricultural area with (in) and without (out) the connectivity factor in the Campestre watershed, Colombo, Paraná, Brazil.*

Alabama (NRCS, 2001)				*Montana* (Fasching, 2006)				*New Mexico* (Flynn *et al.*, 2000)			
Whole		Agric.		Whole		Agric.		Whole		Agric.	
in	*out*	*in*	*out*	*in*	*out*	*in*	*out*	*in*	*out*	*in*	*out*
25	24	93	84	14	11	57	27	14	10	50	35
low	low	very high	high	medium	medium	very high	high	low	very low	extremely high	high

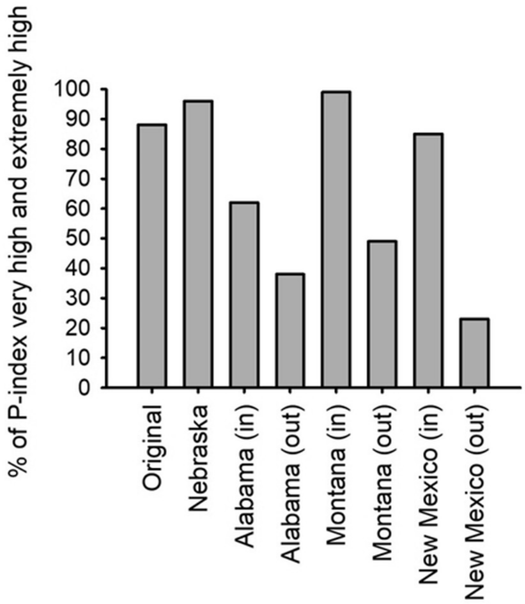

Fig. 5: *Percentage of areas for the agricultural fields with P-index very high and extremely high of versions with (*in*) and without (*out*) the connectivity factor.*

4 Discussion

The low risk of P loss on the whole watershed is explained by the presence of forest vegetation (67 % of the area is occupied by forest vegetation and only 19 % by agriculture). On the other hand, the high risk of P loss for the agricultural area is explained by the steep slopes (more than 70 % of the cropped fields are located on slopes steeper than 13 %). Soil loss and surface runoff are greatly affected by slope, which strongly influences P transport (Eghball & Gilley, 2001). Delaune *et al.* (2004) found a greater effect of surface runoff on P loss in pastures systems. However, in conventional systems, the contribution of soil loss (erosion) is usually higher than water loss (surface runoff) (Gburek *et al.*, 2000). In addition to slope, the high soil P content (Pote *et al.*, 1999) and rates and source of P application (Shigaki *et al.*, 2007) contribute to high risk of P loss.

The greater P-index at sub-basin B than sub-basin A could be explained by land use and connectivity; 24 % of sub-basin B is intensively used for vegetable cultivation, while this only accounts for 8 % in sub-basin A; 41 % of agriculture in sub-basin B occurs on slopes > 20 % and 19 % of the riparian zone is covered by agriculture. In sub-basin A only 6 % of the riparian zone is used for agriculture, on the other hand, 60 % of agriculture occurred on slopes > 20 %. Ribeiro *et al.* (2014), studying the same sub-basins, observed a better water quality at sub-basin A. The transport of pollutants from soil to water is highly related to the land use and soil management (Sharpley *et al.*, 2014).

The connectivity factor (such as distance between cropped fields and water streams and riparian filter strip width) was more important when determining P-index for agricultural areas than at a whole watershed scale, especially because the Campestre watershed has high forest coverage. The increased P-index for versions with connectivity factor can be explained by the lack of riparian native vegetation and by the short distance between cultivated fields and watercourse. Agricultural land closer to the stream and without required riparian vegetation have greater soil and water loss (Nair & Graetz, 2004) and consequently a greater risk of P loss (Flynn *et al.*, 2000; NRCS, 2001; Fasching, 2006).

High vulnerability for P loss (high P-index) on agricultural land in the Campestre watershed highlights the need for improved management practices to control soil erosion and surface runoff (transport factors). It is also necessary to reduce P fertilisation (factor source) avoiding future problems with water contamination (Sharpley & Wang, 2014). In freshwaters, phosphorus is the main nutrient associated with eutrophication, so conservation measures across the watersheds need to be implemented (Sharpley *et al.*, 2014). The P-index was developed to estimate the vulnerability of P loss from soil to waters (Lemunyon & Gilbert, 1993) and it is an important tool for farmers, field staff and watershed planners (Sharpley *et al.*, 2003; Sharpley *et al.*, 2001)

So, the five P-index versions can be recommended as a tool to rank the vulnerability to P loss in surface runoff and subsequently to recommend best management practices. However, as the P-index increased when connectivity factors (distance between cropped fields and the stream and/or riparian filter strip) was included, we suggest to use at agricultural field scale a P-index incorporating connectivity in its framework.

Acknowledgements

The authors thank the National Council for Scientific and Technological Development (CNPq), the farmers from the watershed, and colleagues who helped with the field and laboratory work.

References

Bechmann, M., Krogstad, T. & Sharpley, A. N. (2005). A phosphorus index for Norway. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science*, 55 (3), 205–213.

Bechmann, M. E., Stalnacke, P. & Kvaerno, S. H. (2007). Testing the Norwegian phosphorus index at the field and subcatchment scale. *Agricultural Ecosystems & Environment*, 120, 117–128.

Bertoni, J. & Lombardi Neto, F. (1999). *Conservação do solo*. (4th ed.). Editora Ícone, São Paulo. 355 pp. (in Portuguese)

Brasil (2012). Lei Federal 12.651 Novo Código Florestal Brasileiro. Available at: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm (accessed on: 26 March 2018).

Buczko, U. & Kuchenbuch, R. O. (2007). Phosphorus indices as risk-assessment tools in the U.S.A. and Europe–a review. *Journal of Plant Nutrition and Soil Science*, 170, 445–460.

Caviglione, J. H., Kiihl, L. R. B., Caramori, P. H. & Oliveira, D. (2000). Cartas climáticas do Paraná. Iapar, Londrina, CD.

Correll, D. L. (1998). The role of phosphorus in the eutrophication of receiving waters: A review. *Journal of Environmental Quality*, 27, 261–266.

Couto, R. R., Santos, M., Comin, J., Martini, L. C. P., Gatiboni, L. C., Martins, S. R., Belli Filho, P. & Brunetto, G. (2015). Environmental vulnerability and phosphorus fractions of areas with pig slurry applied to the soil. *Journal of Environmental Quality*, 44, 162–173.

Daniel, T. C., Sharpley, A. N. & Lemunyon, J. L. (1998). Agricultural phosphorus and eutrophication: A symposium overview. *Journal of Environmental Quality*, 27, 251–257.

Delaune, P. B., Moore, P. A., Carman, D. K., Sharpley, A. N., Haggard, B. E. & Daniel, T. (2004). Development of a phosphorus index for pastures fertilized with poultry litter – Factors affecting phosphorus runoff. *Journal of Environmental Quality*, 33, 2183–2191.

Eastman, J. R. (1999). *Guide to GIS and image processing*. Clark University, Worcester. 193 pp.

Eghball, B. & Gilley, J. E. (2001). Phosphorus risk assessment index evaluation using runoff measurements. *Journal of Soil and Water Conservation*, 56, 202–207.

Embrapa (2006). Sistema Brasileiro de Classificação de Solos. 2 ed., Embrapa, Rio de Janeiro, Brasília, DF. Available at: http://livraria.sct.embrapa.br/liv_resumos/pdf/00053080.pdf (accessed on: 26 March 2018).

Engel, B. & Mohtar, R. (2006). Estimating soil erosion using RUSLE and the ArcView GIS. Available at: http://pasture.ecn.purdue.edu/~abe526 (accessed on: 1 June 2010).

Fasching, R. A. (2006). Phosphorus index assessment for Montana. Agronomy Technical Note 77. United State Department of Agriculture – Natural Resources Conservation Service.

Flynn, R., Sporcic, M. & Scheffe, L. (2000). Phosphorus assessment tool for New Mexico. Agronomy Technical Note 57. United State Department of Agriculture – Natural Resources Conservation Service.

Gburek, W. J., Sharpley, A. N., Heathwaite, A. L. & Folmar, G. J. (2000). Phosphorus management at the watershed scale: a modification of the phosphorus Index. *Journal of Environmental Quality*, 29, 130–144.

Heathwaite, L., Sharpley, A. & Bechmann, M. (2003). The conceptual basis for a decision support framework to assess the risk of phosphorus loss at the field scale across Europe. *Journal of Plant Nutrition and Soil Science*, 166, 447–458.

Hooda, P. S., Edwards, A. C., Anderson, H. A. & Miller, A. (2000). A review of water quality concerns in livestock farming areas. *Science of the Total Environment*, 25, 143–167.

Kay, P., Edwards, A. C. & Foulger, M. (2009). A review of the efficacy of contemporary agricultural stewardship measures for ameliorating water pollution problems of key concern to the UK water industry. *Agricultural Systems*, 99, 67–75.

Kleinman, P. J. A., Sharpley, A. N., Noyer, B. G. & Elwinger, G. (2002). Effect of mineral and manure phosphorus sources on runoff phosphorus. *Journal of Environmental Quality*, 31, 2026–2033.

Leinweber, P., Turner, B. L. & Meissner, R. (2002). Phosphorus. *In:* Haygarth, P. M. & Jarvis, S. C. (eds.), *Agriculture, hydrology and water quality*. pp. 29–55, CAB International, Cambridge.

Lemunyon, J. L. & Gilbert, R. G. (1993). The concept and need for a phosphorus assessment tool. *Journal of Production Agriculture*, 6, 483–486.

Lopes, F., Merten, G. H., Franzen, M., Giasson, E., Helfer, F. & Cybis, L. F. A. (2007). Utilização de P-index em uma bacia hidrográfica através de técnicas de geoprocessamento. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 11, 312–317. (in Portuguese)

MathWorks (2017). MATLAB. The language of technical computing. Available at: https://www.mathworks.com (accessed on: 26 March 2018).

Moore, I. & Burch, G. (1986). Physical basis of the length-slope factor in the universal soil loss equation. *Soil Science Society of America Journal*, 29, 1624–1630.

Nair, V. D. & Graetz, D. A. (2004). Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: the Florida experience. *Agroforestry Systems*, 61, 269–279.

NRCS (2001). Phosphorus index for Alabama: A planning tool to asses and manage P movement. Agronomy Technical Note 72. United State Department of Agriculture – Natural Resources Conservation Service. United State Dep.

Oliveira, M. F. M., Favaretto, N., Roloff, G. & Fernandes, C. V. S. (2010). Estimativa do potencial de perda de P através da metodologia "P-index". *Revista Brasileira de Engenharia Agrícola e Ambiental*, 14, 267–273. (in Portuguese)

Pavan, M. A., Bloch, M. F., Zempulski, H. C., Miyazawa, M. & Zocoler, D. C. (1992). Manual de análise química de solo e controle de qualidade. Londrina, IAPAR, Circular 76. (in Portuguese)

Pote, D. H., Daniel, T. C., Nichols, D. J., Sharpley, A. N., Moore, P. A., Miller, D. M. & Edwards, D. R. (1999). Relationship between phosphorus levels in three ultisols and phosphorus concentrations in runoff. *Journal of Environmental Quality*, 28, 170–175.

Ramos, M. R., Favaretto, N., Dieckow, J., Dedeck, R. A., Vezzani, F. M., Almeida, L. & Sperrin, M. (2014). Soil, water and nutrient loss under conventional and organic vegetable production managed in small farms versus forest system. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 115 (1), 31–40.

Reid, D. K. (2011). A modified Ontario P-index as a tool for on-farm phosphorus management. *Canadian Journal of Soil Science*, 91, 455–466.

Renard, K. G., Foster, G. R., Weesies, G. A., Mccoll, D. L. & Yoder, D. C. (1997). Predicting soil erosion by water. A guide to conservation planning with the Revised Universal Soil Loss Equation. USDA. Agricultural Handbook 703.

Ribeiro, K. H., Favaretto, N., Dieckow, J., de Paula Souza, L. C., Minella, J. P. G., de Almeida, L. & Ramos, M. R. (2014). Quality of surface water related to land use: a case study in a catchment with small farms and intensive vegetables production in southern Brazil. *Revista Brasileira de Ciência do Solo*, 38 (2), 656–668.

Roloff, G. & Denardin, J. E. (1994). Estimativa simplificada da erodibilidade do solo. *In:* Resumos da X Reunião Brasileira de Manejo e Conservação do Solo e Água. Florianópolis, SBCS. (in Portuguese)

Rufino, R. L., Biscaia, R. C. M. & Merten, G. H. (1993). Determinação do potencial erosivo da chuva do estado do Paraná através da pluviometria: terceira aproximação. *Revista Brasileira de Ciência do Solo*, 17, 439–444. (in Portuguese)

Santos, R. D., Lemos, R. C., Santos, H. G., Ker, J. C. & Anjos, L. H. C. (2005). *Manual de descrição e coleta de solo no campo*. (5th ed.). Viçosa, Sociedade Brasileira de Ciência do Solo. (in Portuguese)

SBCS (2004). *Manual de adubação e de calagem para os Estados do Rio Grande do Sul e de Santa Catarina*. (10th ed.). Sociedade Brasileira de Ciência do Solo (SBCS), Comissão de Química e Fertilidade do Solo, Porto Alegre. Available at: http://www.sbcs-nrs.org.br/docs/manual_de_adubacao_2004_versao_internet.pdf

Schindler, D. W., Hecky, R. E., Findlay, D. L., Stainton, M. P., Parker, B. R. & Paterson, M. J. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37-year whole-ecosystem experiment. *Proceedings of the National Academy of Sciences USA*, 105 (32), 11254–11258.

Sharpley, A. (1995). Identifying sites vulnerable to phosphorus loss in agricultural runoff. *Journal of Environmental Quality*, 24, 947–951.

Sharpley, A., Jarvie, H. P., Buda, A., May, L., Spears, B. & Kleinman, P. (2014). Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. *Journal of Environmental Quality*, 42, 1308–1326.

Sharpley, A. & Wang, X. (2014). Managing agricultural phosphorus for water quality: Lessons from the USA and China. *Journal of Environmental Sciences*, 26 (9), 1770–1782.

Sharpley, A. N., Mcdowell, R. W. & Kleinman, J. A. (2001). Phosphorus loss from land to water: Integrating agricultural and environmental management. *Plant and Soil*, 237, 287–307.

Sharpley, A. N., Weld, J. L., Beegle, D. B., Kleinman, P. J. A., Gburek, W. J., Moore Jr, P. A. & Mullins, G. (2003). Development of phosphorus indices for nutrient management planning strategies in the United States. *Journal of Soil and Water Conservation*, 58, 137–153.

Shigaki, F., Sharpley, A. N. & Prochnow, L. I. (2006). Animal-based agriculture, phosphorus management and water quality in Brazil: Options for the future. *Scientia Agricola*, 63 (2), 194–209.

Shigaki, F., Sharpley, A. N. & Prochnow, L. I. (2007). Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays. *Science of the Total Environment*, 373, 334–343.

Sparks, D. L. (1996). *Methods of soil analysis. Part 3 Chemical Methods*. Soil Science Society of America (SSSA), Madison.

Suderhsa (2000). *Fotografias aéreas coloridas. Escala 1:30.000*. Instituto das Águas do Paraná. Available at: http://www.aguasparana.pr.gov.br/modules/conteudo/conteudo.php?conteudo=78

Veith, T. L., Sharpley, A. N., Weld, J. L. & Gburek, W. J. (2005). Comparison of measured and simulated phosphorus losses with indexed site vulnerability. *Transactions of the ASAE*, 48, 557–565.

Waltrick, J. C. N. (2011). *Aplicação da metodologia P-index na bacia hidrográfica do campestre-Colombo, PR*. Master’s thesis, Universidade Federal do Paraná, Curitiba, Brazil. (in Portuguese).