Landscape factors of nutrient transport in temperate agricultural catchments

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Abstract

The influence of landscape factors on nutrient fluxes is highly variable, depending on which fluxes dominate and vary in the subject catchment. Watersheds where the input is the most variable source, soil qualities, the proportion of certain land uses, proximity to the water body and runoff determine nutrient transport. In catchments, where variation in chemical and physical conduits and barriers determines the flows, the factors of the landscape pattern also explain the differences in nutrient losses.

Nitrogen, apart from other nutrients, is better determined by factors of agriculture and the qualities of the soil. Due to the relevance of anaerobic conditions in denitrification, one of the specifically important factors is water regime. It has been proposed that the greatest variance among nitrogen losses occurs in small catchments (<5000ha). Attention to that should help address issues of scale in nutrient transport research.

Phosphorus is more strongly connected with physical factors, especially flow conduits and barriers. There is a well established link with the amount of riparian buffers. The proportion of urban land use also has a relatively great influence.
Keywords: landscape, spatial, geostatistics, geochemistry, nutrient transport, nutrient losses, nutrient flux, nutrient flow, nitrogen transport, phosphorus transport, catchment, watershed.

1 Introduction

In this paper we consider landscape as a geo-system or geo-complex, a comprehensive complex of natural (physical, chemical, biological) and anthropogenic factors distinguished at various hierarchical levels (i.e., micro-, meso-, and macro-chores; see [1-6]). Depending on the degree of human interaction, landscape characteristics can be dominated by natural aspects on the one hand or human management on the other hand. In this paper we consider

WIT Transactions on Ecology and the Environment, Vol 104, © 2007 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RM070391

landscape as a geo-system or geo-complex, a comprehensive complex of natural (physical, chemical, biological) and anthropogenic factors distinguished at various hierarchical levels (i.e., micro-, meso-, and macro-chores; see [1-6]). The main natural factors in such a complex landscape system are water, topography, soil, geology and climate conditions, as well as plants (vegetation cover) and animals (fauna). Likewise, the ecosystem approach deals with the same factors as ecosystem components, but in contrast to ecosystems, where all of the relations are considered via biota, the geo-system/landscape concept considers all of the relationships [5]. However, different factors at different temporal and spatial scales play different roles in determining landscape character. Climatic and geological conditions cause the basic natural character of a landscape, whereas topography, soil and vegetation cover are important in the formation of the detailed character of a landscape, and are influenced by human management [7].

In nutrient transport research, the basic landscape unit is catchment. The two basic preconditions for a chemical element to be transported in catchment are: a) availability of material and b) availability of energy. Both, and especially the latter, are directly or indirectly controlled by landscape (complex spatial) factors. Landscape factors are generally accepted and addressed as controls over nutrient fluxes (see [8-11]). Several spatial export coefficients are used (e.g. Nitrogen Index [18]), but such predictions may lack precision because the variability in export coefficients is large. There is no theoretically generalized information about which ecosystem processes are contributing nutrient transport [17]. Empirical associations only varyingly succeed in implicating actual relations [8]. This is the case for a number of landscape-specific reasons, including (a) covariation of factors, (e.g. [8,11]), (b) the existence of multiple, scale-dependent mechanisms (e.g. [8,11]) and (c) autocorrelation (self-dependence) between spatial elements [12]. It is probably due to these problems that most nutrient transport correlation analyses use only the simplest of spatial factors (for example, the percentage of certain land use). More sophisticated and abstract factors, such as FRAGSTATS metrics [13] or watershed area [9], are addressed considerably less often.

The present work was an effort towards a better understanding of the ecosystem processes that drive nutrient transport. The objective of this paper was to give an overview of the literature about the role of landscape (spatial biophysical and biotic) factors on nitrogen and phosphorus fluxes from source areas to surface water. The following questions were asked: a) What are the magnitudes of fluxes that constitute nitrogen and phosphorus transport? b) Which spatial factors have been found to be significant determinants of nutrient transport?; c) What is the relationship between catchment size and the amount of nutrients lost from the catchment?

2 Material and methods

The main sources of literature for this paper were works indexed by the Institute of Scientific Information (ISI) Web of Science for recent sources and literature indexed by Mander and Mauring [14] for earlier sources. Data was collected for the purpose of three analyses: a) a conceptual diagram of nitrogen and phosphorus transportation, b) a display of determination coefficients between nutrient losses and landscape (complex spatial) factors and c) an analysis of the relationship between nutrient losses and catchment size. The following are some relevant comments on the methods:

a) The subject of the conceptual diagram was the nitrogen and phosphorus lost from the root zone of source areas and transported towards the surface water. The inputs to source areas (fertilizers, deposition, nitrogen fixation) and nutrients moved from source areas as crops were not taken into consideration. The transport and transformation of nutrients in surface water bodies was also not considered. The scale of this study was the catchment scale. This means that figures from studies performed at field scale were avoided. Therefore the ranges presented can differ from average field scale records, as there are relatively few nutrient studies at catchment scale. The range of flux magnitudes on the diagram was defined as the quartile values (the recorded values between ½ and 1½ of the mean value). In most cases the extreme values were also presented in the text. In other words, no averaging or recalculation of the previously recorded figures was made. All flux figures are cited, as they were in the literature.
b) Only statistically significant determination coefficients ($p<0.05$) were collected as the data for the analysis.
c) It was difficult to find the data for the analysis at catchment size, as catchment area is mostly not correctly reported or is unclear, at which scale the magnitude of nutrient flux has been estimated (catchment or field). In this paper we only included figures from works where these problems did not occur.

3 Results and discussion

3.1 Landscape factors of nutrient transport

The geochemical concept of elementary landscapes [15] was used as the basis for defining nutrient transport fluxes. According to that, landscape is a centralized system. The association of soil cover and vegetation serves as the centre of the system. While investigating material flows, elementary landscapes are identified as the largest possible areas of uniform soil cover and vegetation. A common topological score of elementary landscapes in temperate agricultural catchments is presented in Figure 1a.

In investigating nutrient transport, special attention is paid to the sensitivity of landscape elements. Particularly sensitive elements (e.g. hill slope hollows) serve as conduits for nutrient fluxes. Resistant elements act as barriers or sinks (e.g. riparian strips for down slope flow). In resistant landscape elements, where nutrients are held for a substantial time, transformations of material occur, and these are controlled by the complex of qualities of the area (e.g. transformation of nitrogen, controlled by tree species and the availability of oxygen) [9].

3.1.1 Landscape factors of nitrogen transport

The concept of excess nitrogen [17] is generally used to address the issues of nitrogen transport. The amount of potential excess nitrogen is commonly associated with the amount of applied fertilizer and escaped waste, which are closely linked to intensive agricultural and urban land use. The leaching of nitrogen into surface water occurs mainly in the condition of permeable (sandy) or acidic soil and absence of slope (Fig. 1b). Depending on these conditions, the rate of leaching is usually 8.8-29.0 kgN*ha^{-1}*y^{-1} [16,19]. Leaching is typical for autonomous landscape elements [15].

In the presence of slope and impermeable soil or artificial ground cover, surface flow dominates in the transportation of excess nitrogen. Depending on the conditions, average surface flow is 3.4-15.9 kgN*ha^{-1}*y^{-1} [16,19]. Surface flow is typical for transit landscape elements [15].

Leaching and surface flow are mostly addressed together as the flow from autonomous landscape units (agricultural fields and urban areas) through transit units (slopes, adjacent to water bodies) to superaquatic landscape elements (riparian forest and grassland) [15]. The flow is much more extensively studied and therefore greater variance can be reported. Most of the estimated or measured fluxes are within 10-154 kgN*ha^{-1}*y^{-1} [19–23], but fluxes of from 1.8 kgN*ha^{-1}*y^{-1} [22] to 3110 and 6270 kgN*ha^{-1}*y^{-1} [21] have been reported from Western European autonomous landscape units to superaquatic (riparian buffer) zone.

Superaquatic landscape units are substantially different from autonomous and transit landscape units in terms of their flat topography, hydromorphic soils (Histic and Histosols), anaerobic condition and natural and seminatural vegetation (forest, shrub and grass). Such areas act as barriers for the fluxes from geochemical transit zones. Due to this specific set of conditions, denitrification and plant uptake occur as the main set of output fluxes. Depending on the availability of nitrogen and the anaerobic condition, the rate of denitrification at catchment scale has mostly been reported to be 15-32 kgN*ha^{-1}*y^{-1} [21,25–27], but fluxes of 400 kgN*ha^{-1}*y^{-1} [28] and more have been recorded. Denitrification in exceptionally aerobic parts of the subaquatic zone [21,29,30] is similar to autonomous landscape units [17]: 5 kgN*ha^{-1}*y^{-1} and below.

Plant uptake in superaquatic landscape units varies considerably depending on human disturbance (harvesting), natural disturbances (flood), the aerobic condition and present plant species. Riparian vegetation is most commonly reported to be able to take up 83-146 kgN*ha^{-1}*y^{-1} [21,31], although significantly smaller fluxes have been recorded [16,31,32]. Vegetation uptake will act as an actual nitrogen flux only in the amount of grass or wood removed by human activities.

Denitrification, plant uptake and the remaining nitrogen retention capacity of a superaquatic riparian buffer is never able to remove all excess nitrogen. Even in sites with a natural or seminatural buffer zone between a nitrogen source area and a surface water body, a range of 0.01-142 kgN*ha^{-1}*y^{-1} [16,19,28,33–52] is reported to enter the water. The uppermost extreme values of more than 20 kgN*ha^{-1}*y^{-1} [19,50–52] are probably fluxes from adjacent slopes without superaquatic buffer zones. In most median cases, the flux is 0.1-9.2kgN*ha^{-1}*y^{-1} [16,28,37–46].

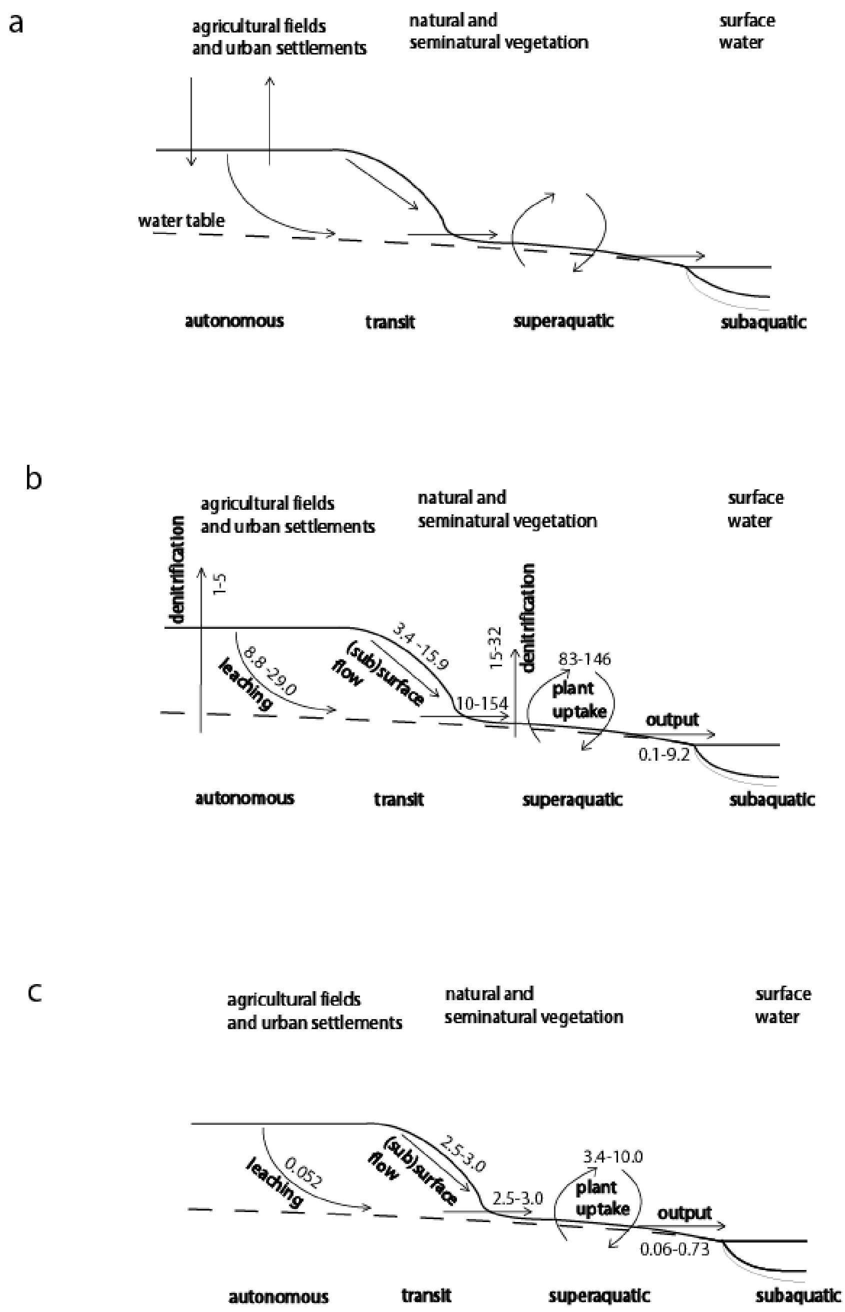

Figure 1: a) A common topological score of geochemical landscape elements; b) mean fluxes of nitrogen [$kgN*ha^{-1}*y^{-1}$]; c) mean fluxes of phosphorus [$kgP*ha^{-1}*y^{-1}$].

The results of the analysis of significant determination coefficients between spatial catchment scale spatial factors of and measured nutrient losses from the watershed are presented in Table 1. A complex index of topography, soil water conductivity and soil depth [55] has been reported to have exclusively high explanatory power (95%) over nitrogen loss. In certain conditions soil moisture regime can explain a very large degree of variance in nitrogen transport [54]. This is probably because soil moisture depends greatly on topography and soil water conductivity in determining denitrification and vegetation. A good example of an abstract but sophisticated landscape factor is the Stream Proximity index by Agnew *et al* [53], defined as the shortest distance to a stream. The precondition for the factor to determine nitrogen fluxes is a small variance in land use and vegetation. In catchments where nitrogen fluxes are controlled more by inputs than by retention in barriers, the proportion of urban or agricultural land use and road density will explain a good proportion of nitrogen loss [11,55]. The same probably goes for the factor of the proportion of natural areas, as a linearly negative function of agricultural and urban areas. Meanwhile factors of landscape pattern such as Edge Density and Mean Nearest Neighbour [55] are more likely to influence nitrogen fluxes in a more mosaic catchment.

The influence of landscape structure is confined by factors of composition, illustrated by a complex factor of edge density and agricultural land use being a good predictor of nitrogen loss [63]. A combination, including edge density, Mean Shape index, contagion, proportion of natural area, the proportion of agricultural land use, the proportion of bogs and mires and the proportion of urban land use, was recorded as the best determinant function of nitrogen transport (Table 1).

A recent study by Burt and Pinay [9] had suggested watershed size to be a complex control of nitrogen transport. The evidence provided by them shows the large variability of nitrogen loss from small watersheds with an area of less than 5000ha, but little variability from the entire river systems. In other words, the signal-to-noise ratio is low in large basins (i.e., subtle changes in land-management practices cannot be detected at the basin outlet), but high in smaller tributaries.

Similar data were presented in this paper (Fig. 2). Although it did not include watersheds larger than 11,000 ha, a slight decrease in variability was noticed from 5000ha upwards.

3.1.2 Landscape factors of phosphorus transport

The main sources of excess phosphorus are fertilizers, manure and human waste. There is a well established link between available phosphorus and agricultural/urban land use. The intensity of leaching depends on soil acidity and permeability (sandiness). It is, however, a minor pathway of transport (0.052 $kgP*ha^{-1}*y^{-1}$ [16]), as a mean of 2.5-3.0 $kgP*ha^{-1}*y^{-1}$ flows from source areas in surface flow and subsurface flow [16,24,56] (Fig. 1c). In the presence of slope and pathways and a lack of vegetation, the flow can be 3.15 $kgP*ha^{-1}*y^{-1}$ [57] and more.

Table 1: Determination correlations between landscape factors and nutrient losses from catchment ($p<0.05$).

	R^2 of N loss [kgN* ha^{-1} * y^{-1}]	R^2 of P loss [kgP* ha^{-1}* y^{-1}]	Source
Single spatial factors			
Runoff	0.41	0.48	Kronvang *et al* [19]
Stream proximity	0.66		Agnew *et al* [53]
Landscape composition factors			
Proportion of urban land use	0.48	0.73	Uuemaa *et al* [63]
Proportion of agricultural land use	0.26		Kronvang *et al* [19]
Proportion of agricultural land use	0.34		Uuemaa *et al* [55]
Proportion of natural areas	0.34		Uuemaa *et al* [55]
Amount of riparian buffers		0.63	Jones *et al* [11]
Topography index (incl. soil)	0.95		Agnew *et al* [53]
Soil moisture	0.89		Young and Briggs [54]
Road density (ammonia)	0.50		Jones *et al* [11]
Landscape pattern factors			
Contagion		0.38	Uuemaa *et al* [55]
Shannon's diversity		0.34	Uuemaa *et al* [55]
Mean nearest neighbour index	0.38		Uuemaa *et al* [55]
Edge density	0.31		Uuemaa *et al* [55]
Flow path length		0.83	Doody *et al* [64]
Combination of composition and pattern factors			
Edge density + agricultural land use	0.42		Uuemaa *et al* [63]
Edge density + Mean Shape index + contagion + proportion of natural area + proportion of agricultural land use + proportion of bogs and mires + proportion of urban land use	0.70		Uuemaa *et al* [63]

In superaquatic conditions (even ground and the presence of natural and seminatural vegetation), plants take up a mean of 3.4-10.0 kgP*ha^{-1}*y^{-1} [16,31]. Depending on these conditions, plant uptake can be up to 13.1 kgP*ha^{-1}*y^{-1} [31]. In most cases only 0.06-0.73kgP*ha^{-1}*y^{-1} escapes from superaquatic landscape units and contaminates surface water [16,19,34,37,39,41]. Depending on topography, soil and vegetation, riparian fields and slopes can emit up to 0.8-11.3kgP*ha^{-1}*y^{-1} [45,50,52,60].

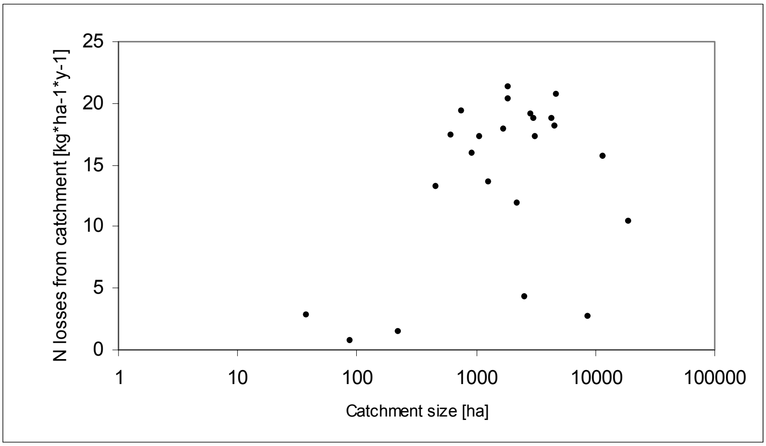

Figure 2: The relationship between catchment size and nitrogen transport.

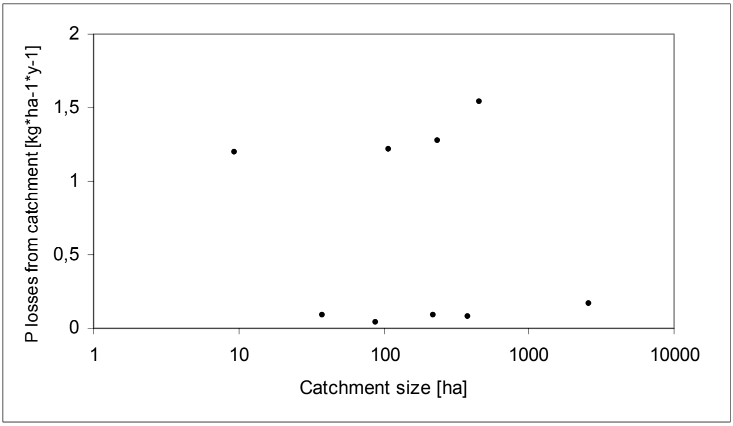

Figure 3: The relationship between catchment size and phosphorus transport.

Phosphorus flux is determined by flow path length as a complex factor of topography, distance [53] and runoff [19] (Table 1). This link is explained by the importance of surface flow in phosphorus movement, as stated above. Another good predictor is the proportion of urban land use in catchment [63]. This could be because human waste (detergents) and industry are great sources of phosphate. The amount (length) of riparian vegetation strips is obviously one of the landscape controls over nutrient fluxes [11]. Landscape pattern, expressed as contagion and Shannon's diversity, can also determine a large proportion of phosphorus fluxes [55]. The reason for this is the amount of physical and chemical barriers present in a heterogeneous landscape.

No conclusion about the effect of catchment size on phosphorus losses could be drawn from the data collected in this paper (Fig. 3). The results instead present two subsets of data: higher values from intensively managed Slapton catchment in Devon, which has steep valley side grasslands [60–62], and lower values from less intensively managed Porijõgi catchment in Estonia [41] and Demnitzer Mühlenfließ catchment in Brandenburg [59], with superaquatic seminatural floodplains.

4 Conclusions

The influence of landscape factors on nutrient fluxes is highly variable, depending on which fluxes dominate and vary in the subject catchment. In watersheds where input is the most variable source, soil qualities [53,55], the proportion of certain land use [11,55,63], proximity to the water body [53] and runoff factors [19] determine nutrient transport (Table 1). In catchments, where variation in chemical and physical conduits and barriers determines the flows, the factors of the landscape pattern also explain the differences in nutrient losses [55,63].

Nitrogen, in comparison with all nutrients, is better determined by factors of agriculture [19,55,63] and the qualities of the soil [53,54,63]. Due to the relevance of anaerobic conditions in denitrification, one of the specifically important factors is soil moisture regime [54]. It has been proposed that the greatest variance among nitrogen losses is in small catchments (<5000ha) [9]. Attention to that should help to address the matters of scale in nutrient transport research.

Phosphorus transport is stronger in connection with physical factors, especially flow conduits and barriers. The link with the amount of riparian buffers is therefore much better established [11], and a stronger dependence of landscape pattern factors has been recorded [55,63,64]. The proportion of urban (industrial) land use also has a relatively great influence [63].

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