

The modelling of soil-process functional units based on three-dimensional soil horizon cartography, with an example of denitrification in a riparian zone

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Abstract

This article aims to propose an approach for estimating the three-dimensional (3D) variability of denitrification. The concept of functional horizons is applied to the process of biological denitrification and 3D soil horizon cartography is used to estimate its spatial variation. On one hand, detailed fieldwork (186 pedological auger holes) was undertaken to map 3D horizon distribution within a 3-ha riparian area using Geographical Information Systems (GIS). On the other hand, three classes of denitrifying capacities were defined according to the distribution of the denitrifying enzyme activity of 51 samples. The relationship between the process of denitrification and the cartography is assessed through soil characteristics, which both differentiate soil horizons and control the process of denitrification: organic carbon and textural fractions. This allows a class of denitrifying capacity to be attributed to each soil horizon. This information was inserted into the 3D soil horizon cartography and the denitrifying functional horizons could be delimited. With this approach, field criteria are used and variations of the 3D distribution of

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denitrification are considered in order to estimate the spatial variation of denitrification within the riparian area being studied.

Keywords: Three-dimensional cartography; Soil horizons; Functional horizons; Denitrification; Riparian area; Prediction

1. Introduction

Disposing of a soil map may be a very helpful long-term tool to manage stressed landscape features such as riparian areas. With traditional soil maps, a cartographic unit represents a type of soil defined by a representative soil profile. However, in riparian areas, the spatial variability of the soil horizon is very heterogeneous and their overlapping quite variable, so much so in fact that any classification made according to a type of soil may not reflect it properly (Finkl, 1980; Gerrard, 1992).

In the last 20 years, soil horizon cartography, which takes three-dimensional (3D) variability of soil horizons into consideration, has been developed (Girard, 1983, 1989; King, 1986; Pereira and FitzPatrick, 1998; Ruellan et al., 1989). Employing soil horizons in the case of the soil of a Swiss floodplain, Mendonça Santos et al. (2000) have established a framework allowing two complementary ways of visualizing soil: maps of horizon or a combination of horizons thickness and cross-sections. This allows the map user to perceive the lateral, longitudinal and vertical spatial variability of the soil or of its horizons, which correspond to Kraak's (1998) definition of a 3D map.

Soil horizons are generally identified in the field, on the basis of differences in texture, structure, colour, presence of mottles and many other, mainly visual, characteristics. However, soil horizons or groups of soil horizons may be related to functional aspects which are not used in the horizon identification such as extractable plant nutrients and physical characteristics (Strong and La Roi, 1988) or hydraulic functions (Wösten et al., 1985). These horizons or groups of horizons that are similar in respect to the particular function in question are called functional horizons (Wopereis et al., 1993). Relating soil functional aspects to soil horizons allows extrapolation of these aspects in areas where no direct measurements have been carried out but where the succession of the soil horizons is known. This may be a good alternative to estimating the variability of soil functional aspects, which may be expensive and time consuming to measure.

In this study, we will combine two approaches; the concept of functional horizons applied to the process of biological denitrification and the use of Mendonça Santos et al. (2000) framework to estimate its spatial variation. Several authors have already demonstrated the importance of denitrification on the role that riparian areas play in removing nitrate from subsurface water before it enters the stream (Jordan et al., 1993; Lowrance, 1992; Schipper et al., 1993). However, a need for high-resolution soil maps (Nelson et al., 1995), gaps in the study of 3D variations of the process (Martin et al., 1999), as well as in its regionalization on the field scale (Groffman et al., 1992b) have been emphasized.

The principal aim of this study is to propose an approach for estimating the 3D variability of denitrification. The following steps will be necessary: (i) to define denitrifying functional horizons and (ii) to delimit denitrifying functional horizons using 3D soil horizon cartography.

2. Material and methods

2.1. Site description

The site is located in western Switzerland and belongs to the geographical unit constituted by the Swiss Plateau (46°36'N; 6°24'E). It is adjacent to the River Morand and lies at an altitude of about 660 m. The site consists of two parts: a slope of about 3% declivity and an adjacent flat riparian zone. The surface on which the soil cartography was carried out is about 3 ha in extent (Fig. 1a). Between 1961 and 1990, mean monthly temperatures range from 0.8 to 19.0 °C and the mean annual rainfall is 950 mm.

The site includes a grassland meadow, two wooded areas and an arable area (Fig. 1a). The extensive meadow is cut twice a year and grazed in autumn (cows). The meadow is composed of both graminaceae (*Bromus hordeaceus*, *Dactylis glomerata*, *Holcus lanatus*, *Lolium multiflorum*, *Poa trivialis*,...) and of common dicotyledon (*Ranunculus acris*, *Taraxacum officinale*, *Trifolium* spp.,...). The eastern wood is part of an alluvial forest; *Alnus glutinosa*, *Fraxinus excelsior* represent the dominant tree species in it. In the western wooded part, *Epicea abies*, *Betula pendula* and *F. excelsior* represent the dominant tree species. The arable area south of the road is subject to crop rotation.

The research area is situated on recent glacial deposits (Würm), in which three different geological formations can be found. The first is a silty-clayed till formation and the second corresponds to silty colluvium. The last formation is an aquifer, containing circulating water, and which consists of fluvioglacial materials that fill a furrow cast in the till (Parriaux and Maître, 2001).

2.2. Methodology

The presented approach (Fig. 2) is based on two research surveys—cartography and denitrification—which are completely independent from one another and can be carried out in whichever order is most convenient. Then, the following steps are undertaken to estimate the spatial variability of denitrification.

- (i) Firstly, denitrifying functional horizons are identified. The first step (i-a) is to select among the soil parameters used to identify soil horizons, the one, which may control the denitrification process and to characterise this relationship. The activity of denitrifiers is controlled by the availability of oxygen, organic carbon compounds and nitrogen oxides as well as pH (Knowles, 1982). Therefore, textural fractions, organic and mineral carbon content which all differentiate the soil

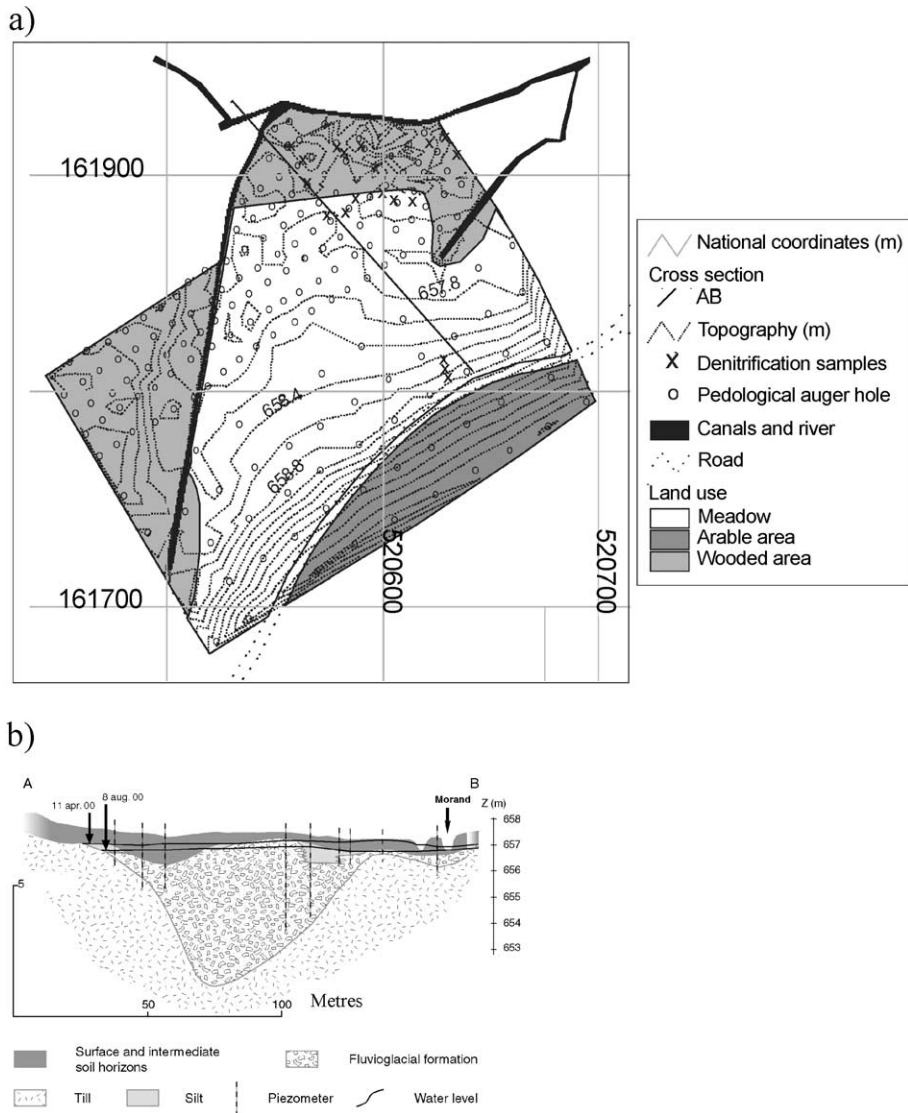


Fig. 1. (a) Location of the 186 pedological auger holes, 18 denitrification sampling points and AB geological cross-sections (Piezometers are not indicated). Map of the topography and land cover. (b) Cross-section (AB) of geological settings (Parriaux and Maître, 2001).

horizons may strongly influence the denitrification process. Indeed, texture and coarse elements control oxygen availability, organic matter content is strongly related to organic carbon compounds and nitrogen oxide availability. Finally, organic matter and carbonate content influence pH. Nevertheless, there is no linear relationship between these physico-chemical parameters and the denitrification

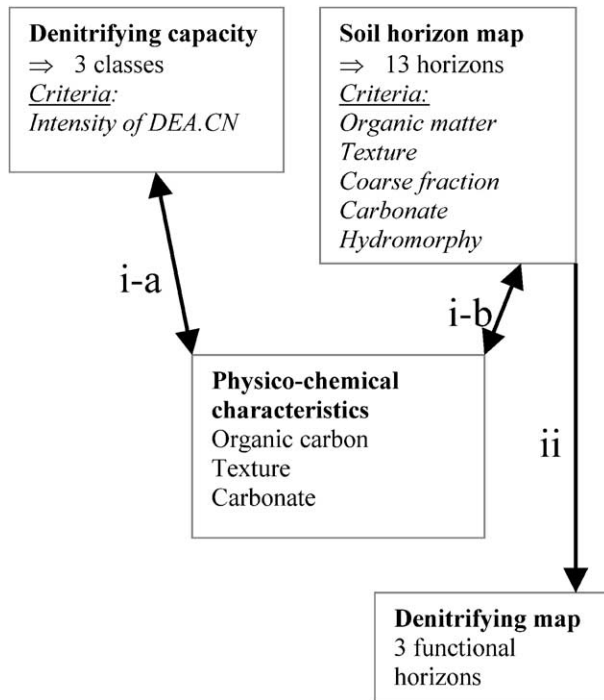


Fig. 2. Scheme of the approach used in this paper, see Section 2.2 for explanations.

process (Ashby et al., 1998; Barton et al., 1999). Therefore, a principal components model (PCA) is built using carbon (organic and mineral) and texture (fine and coarse fractions) data measured during the denitrification survey in order to assess how these parameters influence denitrification. All statistical analyses were performed using S-Plus 2000 for Windows (Mathsoft, 1999) and correlation matrices were used to build the PCA model. Then (i-b), the denitrifying capacity of the different soil horizons is predicted. For that, a new data set is used: carbon (organic and mineral) and textural fraction data measured on six representative samples of each identified soil horizon. These data are positioned in the principal component space built previously, using the “predict” function of S-Plus (Mathsoft, 1999). This function allows to calculate the image of the new data set under the principal components transformation. Then, the projection of both data sets together allows us to graphically regroup samples issued of the new data set to the closest samples for which the denitrifying capacity is known.

- (ii) In order to delimit denitrifying functional horizons, the details of the spatial pattern of the soil horizons (3D soil horizon map) are combined with the denitrifying capacity details. This allows diverse maps, which illustrate the spatial variability of denitrification to be produced. These maps will be discussed in this paper.

2.3. Soil horizon cartography

The 3D soil horizon map was realised using GIS software (ARC/INFO) (ESRI, 1995, 1996) as presented by Mendonça Santos et al. (2000).

2.3.1. Field survey

The sampling network was composed of two squared grids: a 10-m grid in the northern part of the site and a 20-m grid in the southern one (Fig. 1a), because soils were more heterogeneous towards the north than in the south. Hence, a total of 186 points were surveyed using a 1.20-m-long pedological (core sampling) drill. Indeed, the installation of piezometers for a hydrogeological survey (Parriaux and Maître, 2001) showed that soil organic and organo-mineral horizons were not deeper than 1.20 m but that the thickness of the different mineral horizons could reach several metres (Fig. 1b). Consequently, it was decided not to delimit the thickness of these mineral horizons in the context of this cartography.

At each survey point, the thickness of each soil horizon, except the mineral ones, was recorded. Each differentiated soil horizon corresponds to a homogeneous unit defined visually in the field by semi-quantitative criteria such as hydromorphy, organic matter and carbonate content, textural fraction (fine and coarse). Horizon nomenclature were allocated according to “A sound reference base for soil” (A.F.E.S., 1998). Where required, a suffix was added according to soil texture.

2.3.2. Landform modelling

As a preliminary, eight reference points were set using the Global Positioning System (GPS) in order to link our coordinates to the Swiss national coordinate system. Then, *X*, *Y* and *Z* coordinates were determined for all soil survey points using a theodolite connected to a portable computer. So as to be able to model the landform, further coordinates were determined in addition to the soil survey points. These new points serve in identifying specific landform features (unevenness, rivers, canals, road, forest limits). Elevation data were interpolated using a Triangular Irregular Network (TIN) and from this, a Digital Elevation Model (DEM) was built.

2.3.3. Spatial patterns of soil horizons

Thickness maps of horizons are obtained by interpolating measured thickness values for each different horizon. The characteristics of our data set—regular grid, dense sampling, and relatively precise measurements—made the use of the TIN interpolation technique appropriate.

Cross-sections were obtained using the following steps. Firstly, the elevation value of the bottom of each horizon was calculated on the basis of the surface elevation value and the thickness of the horizons located above the one being studied. Hence, a vertical order of the horizons position needed to be defined. The soil formula method described in FitzPatrick (1986) and applied for example by Lahmar et al. (1989) was used. Secondly, the TIN interpolation method was employed to generate isolines and filled contour areas corresponding to the bottom of each horizon. Finally, the “Profiling” procedure in ARC/INFO allowed a cross-section to be generated showing the bottom line of each horizon along any line crossing the investigated area.

2.4. Denitrification survey

Denitrification data was obtained in the context of a European project on nitrogen removal (Pinay and Burt, 2001) which focuses on the forested and meadowland of the near stream area. An additional sampling location was added in order to sample the upper meadowland too. But the western part, as well as the arable land, was not considered for the denitrification study. The 18 sampling points had to be concentrated on a number of fenced areas (Fig. 1) so as to avoid faecal contamination from cattle and due to farmer (un)willingness. Denitrification rates were measured once in December 1999 so that all samples, taken from any depth, benefit from the same conditions. Absence of vegetation uptake means that plants have no effect on nitrate availability and all layers are waterlogged. Within each sampled profile, depth of sampling was chosen so that the sample was representative of one homogeneous soil layer—these samples were not attributed to soil horizons identified by the cartography. Altogether, the in situ denitrification rate and four types of denitrifying enzyme activity (DEA) (Table 1) were measured on 54 samples and technical limitations left it to 51 samples.

Denitrification rates were measured using the acetylene inhibition method (Yoshinari and Knowles, 1976). Denitrifying enzyme activities (DEA) were measured for each sample using Smith and Tiedje (1979) procedure. The different incubation conditions allow us to determine whether one or more of the substrates can also limit denitrification at the sampling site (Tiedje et al., 1989). The 250 ml flasks were capped with rubber serum stoppers and then soil samples (30 g) were amended with acetone-free acetylene to bring atmosphere concentration to 10 kPa (10% V/V). Gas was sampled from the headspace following 2- and 4-h intervals for in situ denitrification rates and 4 and 8 h intervals for DEA. Gas samples were analysed for nitrous oxide using a Perkin-Elmer model 8500 gas chromatograph fitted with a Porapak-Q column operating at 60 °C and an electron capture detector. A mixture of argon and methane was used as the carrier gas at a flow rate of 20 ml min⁻¹.

All the denitrification rates did not present a normal distribution and therefore Wilcoxon signed rank tests were performed to identify which factors (anaerobiosis, availability of carbon or nitrogen) limit denitrification.

Table 1
Incubation conditions for measurements of in situ denitrification rates and four types of denitrifying enzyme activity (DEA)

Denitrification treatment	Anoxic (N ₂) atmosphere	Amendment g ⁻¹ fresh soil	
		4 mg glucose-C	10 µg KNO ₃ -N
In Situ	no	no	no
DEA.a	yes	no	no
DEA.C	yes	yes	no
DEA.N	yes	no	yes
DEA.CN	yes	yes	yes

2.5. Soil physico-chemical analysis

All soil samples (51 from the denitrification survey and 66 from the soil horizon cartography) were dried at 105 °C for 24 h and then sieved through a 2-mm mesh. Larger elements were weighed in order to determine coarse fraction (Coarse). After the destruction of organic matter with hydrogen peroxide and dispersion in diluted sodium pyrophosphate, texture (Clay: A, Silt: L, Sand: S) was measured using the classic sedimentation technique (Robinson pipette). Total carbon content was measured by means of 1000 °C combustion under oxygen flow using a carbon analyser (Casumat 8-Adge, Wösthöff, Germany). Mineral carbon content (Cmin) was determined using the same analyser after dilution in phosphoric acid. Organic carbon content (Corg) was calculated from the difference between those two results. Bulk density of each soil horizon was measured during pit excavation with the core method.

2.6. Denitrifying map

An attribute corresponding to the denitrifying capacity is added to the definition of each soil horizon. Then soil horizons with the same denitrifying capacity are pooled together to delimit the denitrifying functional horizons. The procedure for producing thickness maps and cross-sections of denitrifying functional horizons is similar to the one described for the soil horizons. Volumes of functional horizons can be calculated through the “area and volume statistic” function in ARC/VIEW. Finally, for each sampling point of the cartographic survey, potential nitrogen emission of 1 m² of soil is quantified considering the DEA.CN rate as well as the thickness and the bulk density of each observed soil horizon (not mineral horizons). Then extrapolation, for example using TIN, allows the variation of potential nitrogen emission per square metre within the area of interest to be mapped based on DEA.CN.

Table 2
Description of the 13 identified soil horizons according to semi-quantitative field criteria

Name of horizons	Oxydo-reduction spot (%)	Coloured by organic matter	HCl effervescence	Estimation of clay content (%)	Estimation of > 2 mm fraction (%)
Anca	2–20	black and fibrous aspect	visible	10–30	<2
An	2–20	black and fibrous aspect	no	10–30	<2
A	<2	much	no	10–30	<2
Acah	<2	much	visible	10–30	<2
LA	<2	little	no	30–50	<2
S	2–20	little	no	30–50	<2
ADc	transition between An and G or Dm horizon				
ADs	transition between An and Dx horizon				
G	grey or greenish color	little	no	30–50	<2
Dl	2–20	not	strong	10–30	2–25
Dx	<2	not	strong	< 10	>50
Dm	2–20	not	audible	30–50	25–50
Dmca	2–20	not	strong	30–50	25–50

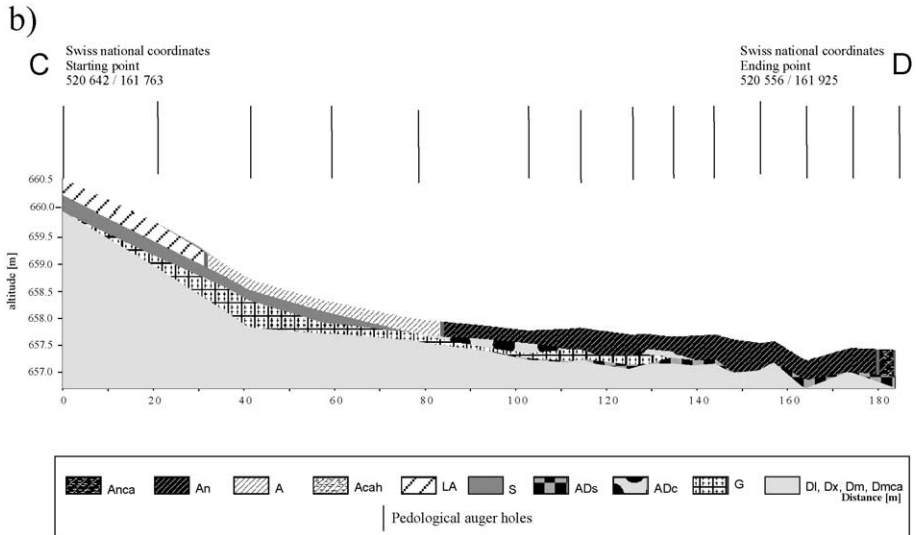
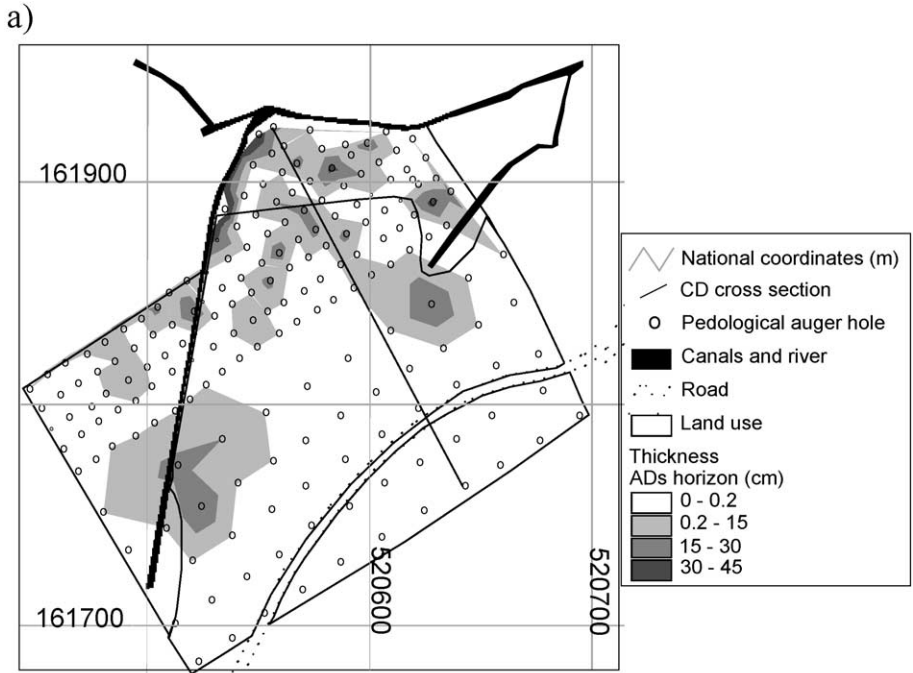


Fig. 3. (a) Thickness map of the ADS horizon, location of the CD cross-section. (b) CD cross-section of soil horizons (since spatial variability of the mineral horizons was not delimited they are presented as a single unit in this cross-section), vertical exaggeration: 12 × .

3. Results

3.1. 3D soil horizon cartography

Based on visual semi-quantitative criteria, 13 soil horizons were identified (Table 2). Four of them were mineral horizons and correspond to the geological formation described above. Dx describes the fluvio-glacial deposits, Dm, as well as Dmca, describes the silty-clayed till formation and D1 describes the silty colluvium. The spatial variability of the different soil horizons is quite high. For example, ADc and ADs—transition horizons—form lenses that appear locally especially in the north and west parts of the investigated site as is illustrated for ADs horizons (Fig. 3a). On the cross-section (Fig. 3b), we can also remark that S (structural horizon) and G (reduced horizon) are more continuous than the transition horizons but are especially located in the upper part of the site. It also appears that thickness of surface horizons (LA, A, An, Anca) increases from upstream to downstream.

3.2. The process of denitrification; relationship with physico-chemical properties

The distribution of DEA.CN rates from 51 individual cores—coming from all over the site—is positively skewed, consisting of many low values. DEA.CN values are comprised between 0.28 and 1042.12 $\text{ng N g}^{-1} \text{h}^{-1}$ and the coefficient of variation is 120%.

Presentation of DEA.CN data in ascending order (Fig. 4) allows the separation of samples into three classes. The first class contains very low values; its upper boundary is set at 25 $\text{ng N g}^{-1} \text{h}^{-1}$, which marks the point at which the gap between two adjacent values in the sequence becomes greater. The second gap sets the second limit (200 $\text{ng N g}^{-1} \text{h}^{-1}$) defining the upper boundary of class 2 and the lower boundary of class 3. It is

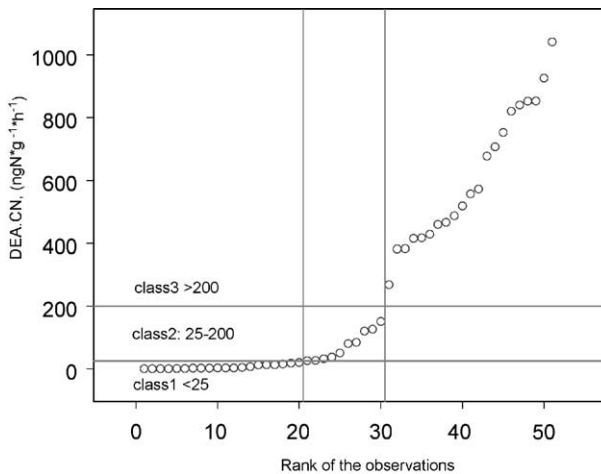


Fig. 4. Definition of denitrifying capacities classes according to 51 results of denitrifying enzyme activity with carbon and nitrate amendment under anaerobic atmosphere (DEA.CN).

worthwhile to note that the two limits in question define the same number of observations around the median ($81 \text{ ng N g}^{-1} \text{ h}^{-1}$).

We tested for a positive effect (p -value < 0.05) of the creation of an anoxic atmosphere between DEA.a and in situ and then for a positive effect of the different amendments between DEA.a and, respectively DEA.C, DEA.N and DEA.CN. The creation of anoxic atmosphere enhances the denitrification rate within each class (Fig. 5). Indeed, the Wilcoxon signed rank test emphasizes a significant positive effect of the creation of anoxic atmosphere on denitrification rates within all classes (p -value: class 1 < 0.0001 , class 2 = 0.001, class 3 < 0.0001). Other than that, response to different incubation conditions is different between each class. In class 1, all denitrification rates are very low and neither the addition of glucose (p -value: 0.9954) nor nitrate (p -value: 0.1162), nor both together (p -value: 0.4864) has any significant effect on these rates. In class 2, only addition of both organic carbon and nitrate significantly enhances denitrification activity (p -value: 0.001). Finally in class 3, denitrification rates are the highest for any given assay. Given natural nitrate concentrations, carbon does not limit denitrification activity (p -value: 0.4864). In comparison, addition of nitrate has a significant effect on denitrification rates (p -value: 0.0036). The denitrification rates become even higher when both substrates are added simultaneously.

The PCA allows us to explain how the three denitrifying classes are related to different soil properties (Fig. 6a). The first component discriminates the three classes whereas the second one improves discrimination between class 2 and the two others. Some samples with a denitrification class of 1 or 2 are positioned among the samples of class 3. This can be due to differences of soil properties between the sub-sample used for denitrification measurements and the one used for textural and carbon analysis. The first component of the PCA, which explains 61% of the variance, mainly contrasts (Fig. 6b) samples rich in clay (A) and organic carbon fractions (Corg) with samples rich in sand (S) and coarse

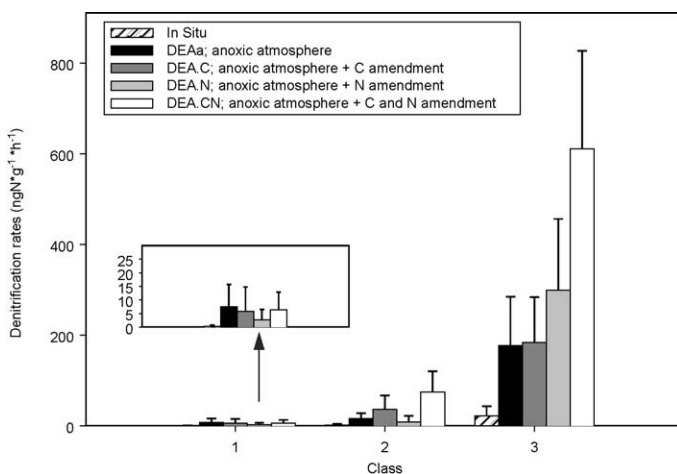


Fig. 5. Mean and standard deviation of the in situ denitrification rate and the four types of DEA according to denitrifying capacities classes (class 1: $\text{DEA.CN} < 25 \text{ ng N g}^{-1} \text{ h}^{-1}$, class 2: $25\text{--}200 \text{ ng N g}^{-1} \text{ h}^{-1}$, class 3: $> 200 \text{ ng N g}^{-1} \text{ h}^{-1}$).

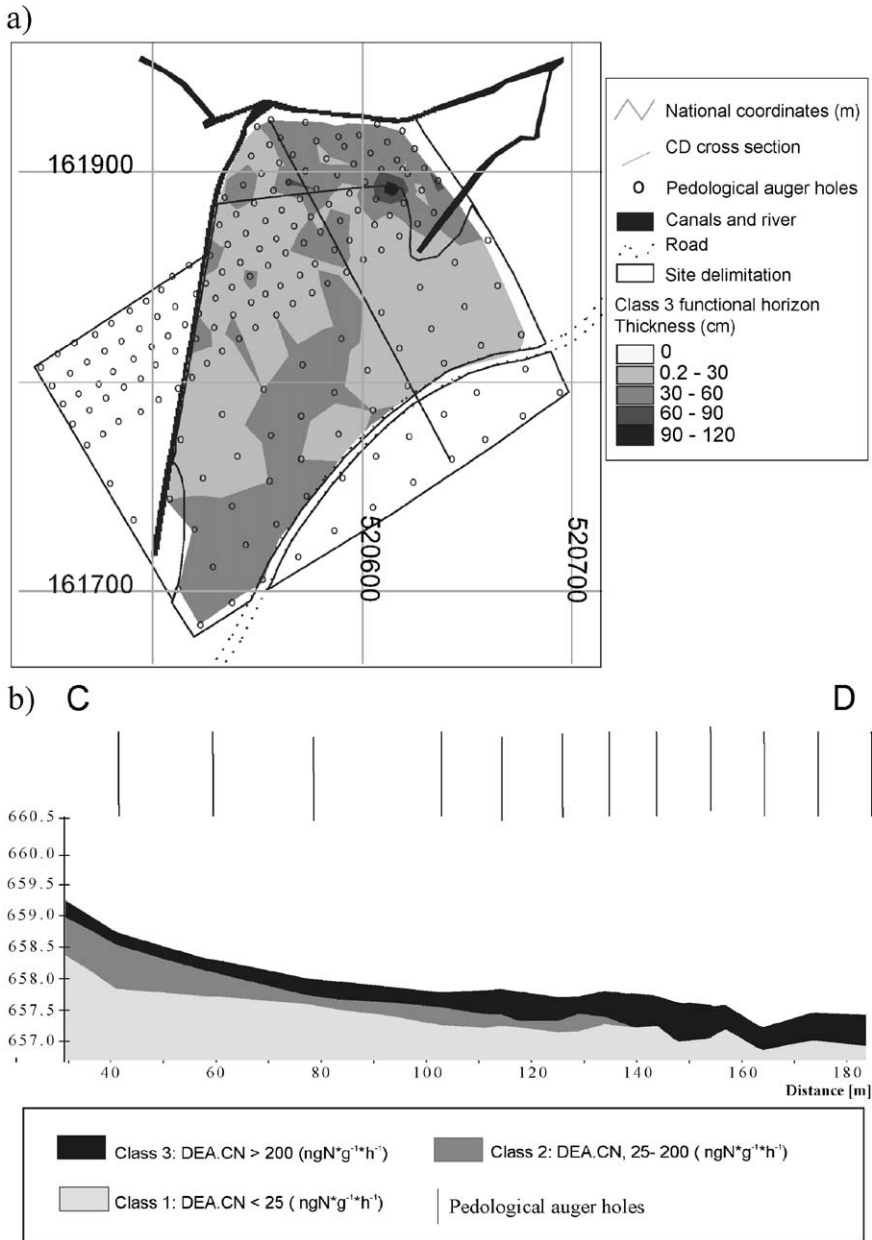


Fig. 7. (a) Thickness map of class 3 denitrifying functional horizons, location of the CD cross-section. (b) C–D cross-section of denitrifying functional horizons, vertical exaggeration: $12 \times$.

Table 3

Estimation of the contribution of each soil horizon belonging to classes 3 (DEA.CN>200 ng N g⁻¹ h⁻¹) and 2 (DEA.CN: 25–200 ng N g⁻¹ h⁻¹) denitrifying functional horizons to the potential nitrogen emission within the studied site

Class	Horizon	Volume (m ³)	Bulk density (g cm ⁻³)	DEA.CN (ng g ⁻¹ h ⁻¹)	DEA.CN (mg N m ⁻² day ⁻¹)
3	Anca	112	0.7	611	50
	An	3175	0.7	611	1402
	A	3146	0.9	611	1871
	Total class 3	6433		Total class 3	3322
2	S	1801	1.1	75	154
	ADc	696	0.8	75	42
	G	3382	1.3	75	333
	Total class 2	5878		Total class 2	529

located close to the third denitrifying class. Data obtained from samples representative of horizon S, G and ADc is located near class 2 denitrifying data. Finally, samples issued from ADs and geological horizons (Dx, Dm, Dmca, DI) is projected near class 1 denitrifying data. An attribute corresponding to the denitrification class is then added to the description of each horizon.

3.4. Spatial variability of denitrification

Soil horizons with the same class of denitrification are pooled together which allows denitrifying functional horizons to be delimited. Denitrifying class 3 functional horizons, which correspond to the amalgamation of surface soil horizons, present increasing

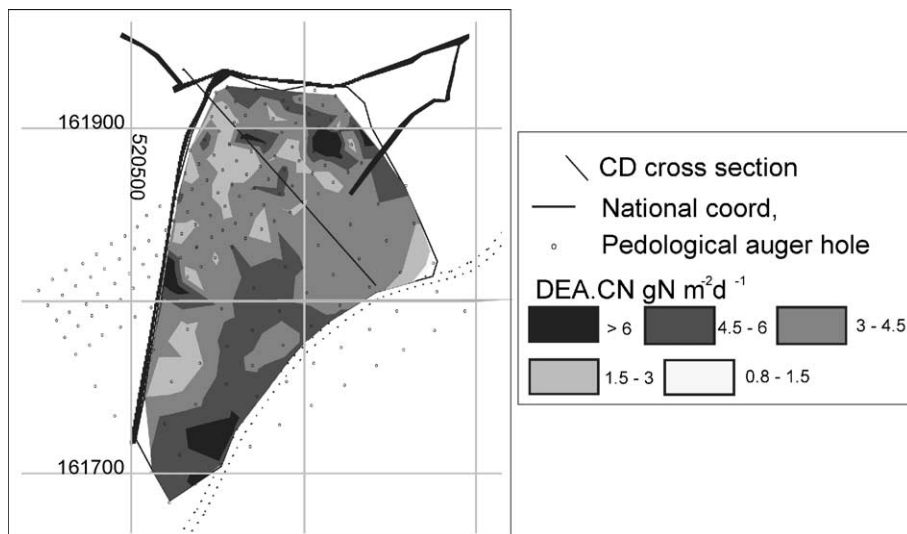


Fig. 8. Estimated spatial variability of the potential nitrogen emission (DEA.CN) within the studied site considering classes 3 and 2 denitrifying functional horizons.

thickness from the upper to the bottom part of the site (Fig. 7a). There are no denitrifying class 2 functional horizons in the bottom part and its thickness is greatest at the southeast part of the study area (Fig. 7b). However, over the whole of the area, volumes of denitrifying classes 1 and 2 functional horizons are quite similar and total DEA.CN ($\text{mg N m}^{-2} \text{ day}^{-1}$) due to the first one is much higher than DEA.CN due to the second one (Table 3). Finally, a map illustrating the variability of DEA.CN due to classes 2 and 3 functional horizons is produced. DEA.CN is quite variable over the area, ranging from 0.8 to over $6 \text{ mg N m}^{-2} \text{ day}^{-1}$ (Fig. 8).

4. Discussion

4.1. Definition of functional horizons

A DEA.CN assay is a good indicator to use as a first descriptor of the denitrification process because it reflects the environmental history of the site from which the soil sample was taken (Tiedje et al., 1989) and is also strongly related to annual denitrification N loss (Groffman and Tiedje, 1989). DEA.CN results are in the range of what was measured on the Garonne alluvial soils (Pinay et al., 2000) and on poorly drained soils of riparian forests in the northern eastern part of USA (Groffman et al., 1992a). Both studies also consider soils from different locations and depths.

Looking at how the different (DEA) denitrification rates behave allows us to describe the denitrification process as a whole and therefore to characterize the different types of denitrification capacity encountered on our site. Then the PCA explains the interactive relationship between the physico-chemical parameters and denitrifying capacity. Firstly, the influence of organic carbon content on the denitrifying capacity is underlined. In class 1, denitrifying enzyme activity (DEA.CN) is very low. Glucose addition has no effect because there are very few operational denitrifying enzymes. In class 2, which corresponds to samples with intermediate organic carbon content, both carbon and nitrate availability limit denitrification. The highest denitrifying enzyme activity (DEA.CN), class 3, is associated with samples possessing high organic carbon contents. In this class, nitrate availability limits denitrification activity. The role of organic carbon availability on denitrification was similarly demonstrated either by emphasising a correlation between total organic carbon (Beauchamp et al., 1980; Burford and Bremner, 1975) or by showing the influence of adding carbon on denitrification activity (Ashby et al., 1998; Schnabel et al., 1996). Secondly, on the one hand, a high denitrifying capacity is related to finely textured samples, while, on the other hand, denitrification rates were significantly improved by the creation of an anaerobic atmosphere in all classes. These two results tend towards the same conclusion since, with the same amount of organic matter, the creation of anoxic atmosphere in soil is favoured by a fine texture (Papendick and Campbell, 1981). This positive influence of fine texture on denitrification rates has already been observed in previous studies (Groffman and Tiedje, 1989; Pinay et al., 1995).

Based on the variation of organic carbon-matter and texture, a class of denitrifying capacity can be attributed to the 11 identified soil horizons within the study area.

Quantitative analysis of these parameters is necessary to confirm the double role of these parameters on both identification of soil horizons and control of the denitrification process. However, once this role is established, field criteria can be used to predict variation of the denitrifying capacities between the different horizons.

Another way to proceed is to predict the denitrifying capacity directly from organic carbon and texture variation. But often, as in the case of denitrification, no linear or univariate relation exists between the target process and the soil variables. Soil horizon classification is a way of pooling soil variables and integrating this multivariate relation. On the other hand, the denitrifying capacity could have been measured in each horizon but this assumes that the map is available before the denitrification survey is carried out. Our approach permits both surveys to be realised in whatever order is the most convenient. Furthermore, it allows us to identify and concentrate on the criteria influencing the studied process. In our case, the 11 identified soil horizons in the study area are pooled into three denitrifying functional horizons.

4.2. Delimitation of functional horizons

3D soil horizon cartography demonstrably provides a flexible and powerful way of visualising the soil 3D pattern. Applied to the concept of functional horizons, it also permits the 3D pattern of a process—denitrification in this case, to be estimated. Thickness maps of different soil horizons can be combined to produce thickness maps of functional horizons. In fact, knowledge of the variation of thickness in one or a combination of soil horizons is important for other aspects such as landscape management (Boer et al., 1996) or agronomic concern (Verhagen and Bouma, 1998; Wopereis et al., 1996). The cross-section offers an alternative manner of visualizing the distribution and interrelation of both soil and functional horizons. It shows how spatial variations of soil horizons induce spatial variation of denitrifying functional horizons and how the vertical distribution of denitrification varies within the riparian area.

Knowing how much nitrogen is potentially denitrified per square metre of riparian area rather than per kilogram of soil is more useful in terms of landscape management. However, the vertical distribution of denitrification has to be integrated rather than considering one constant depth over the whole of the site. In fact, utilisation of GIS offers numerous calculation possibilities. Moreover, storage of information in a database allows us to combine information about both soil and functional horizons. For example, calculation of the volume of each soil horizon could be combined with the knowledge of their denitrifying capacity. This allows the relative influence of two functional horizons on the potential removal of nitrogen due to denitrification to be compared within the area of interest. Within the riparian area, the denitrifying functional horizon class 3 has the potential to remove considerably more nitrogen than the denitrifying functional horizon class 2. Finally, although without validation, we could estimate the spatial variation of potential nitrogen removal while considering the variation of the 3D distribution of denitrification, which is predominant. A validation step would require additional measurements of denitrifying enzyme activity at different locations and depths. The comparison of measured data to estimated ones would allow us to appreciate the reliability of our approach.

In addition, the GIS provides the possibility of studying the spatial relationships between the process being studied and other features. An interesting perspective concerning denitrification in riparian areas is the addition hydrogeology information, which is of great importance on the efficiency of the nitrogen removal in subsurface water (Gilliam, 1994; Hill, 1996).

5. Conclusion

The influence of organic carbon and texture on variation of denitrifying capacities—intensity and limiting factors—within riparian areas is confirmed. These parameters among other soil characteristics differentiate soil horizons, which allows us to attribute a denitrifying capacity to the soil horizon. Soil horizons offer an integrative vision of the spatial variation of different soil characteristics. Then, based on functional horizons it is possible to estimate variation of the denitrification process with field criteria. This approach could be applied to many processes of which expression varies between soil horizons such as trace metal behaviour (Fujikawa et al., 2000) or pesticide transport (Mallawatantri et al., 1996) as long as a relationship between the process and soil characteristics which differentiate soil horizons can be established. Potentially, the finer the horizon description is, the more the variation of the process can be characterized. This is especially interesting when measurement of the process is difficult to carry out or expensive.

The functional horizon map presented is supported by GIS tools, which offer numerous possibilities. The vertical distribution of the process can be considered, many processes can be delimited together and their interactive relationship or influence of landscape features on them can be studied. Hence, in riparian areas but also other complex areas this approach offers a great potential for the better understanding of soil processes or for management decisions.

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