Study of soil–vegetation relationships on the Butte Montceau in Fontainebleau, France: Pedagogical exercise and training report

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ABSTRACT

This article illustrates a short training course for students at the Master’s level, which explores relationships between plants and soil. It takes place in the Forest of Fontainebleau (France), where a reception centre with a large room (30 m2) is located containing a Berlese equipment, and many microscopes. On the first day, students are accompanied by their professors in the field and visit the four sites which are located along an ecological transect. Vegetation and soils at each site are presented to them by specialists. In the laboratory, indications are written on a black board, explaining how to use relatively simple tools for biological investigations (microscopes, GPS, Berlese funnel, photometer, flora and fauna guides…). Students then are divided into 4 groups of 4-6 students. Each group is assigned a site which is then described and analysed. At the end, each group produces a written report. Are the measured parameters interrelated within each site? Are there functioning principles that may distinguish the four stations? Three professors are always present and accompany the students in the field or in the laboratory so as to provide help when necessary. After a brief moment of uncertainty, students are able to quickly organise themselves and after three days identify the essential elements of these ecosystems. They also learn how a real biologist observes a forest ecosystem. They discover that plants, soil and animals are inter-connected and form a natural functioning system. Students thus learn that nonetheless, it is difficult to have clearly identified boundaries between the investigated forest stations, because the gradient between them is gradual and ecologically indefinite.

1. Foreword

This study is a pedagogical exercise, part of the academic course SOLT, proposed yearly by Paris-Saclay and Pierre et Marie Curie Universities (France) in the Biodiversity, Ecology, and Evolution Master. The training course takes place at the Station d’Ecologie Forestière de Fontainebleau-Avon (Université de Paris 7, Diderot).

The aim of the course is to give students an opportunity, through field experience, to observe and measure the main ecological variables in a forest ecosystem. Faced with an ecological question, students develop ways to answer it while dealing with field constraints: what can be measured, with what means, and for what purpose?

SOLT is a five-day training course divided into three phases: 1) field work, after a brief explanation recalling the content of previous courses, collection of vegetation and soil data (about 12 h); 2) data analysis in a training room at the Ecological Station of Fontainebleau-Avon (12 h);
3) statistical analysis of data and report writing (16 h).

Even if the report has the structure of a scientific paper, its content has the value of only a few days of training experience, not one of a scientific publication. It lacks precision in the measurements (use of field tests for chemical data, lack of time for necessary scientific field and laboratory investigations, first time experience for many students to analyse a soil profile or make a phytosociological sampling list…). The report is also a training experience that places them in front of the difficulties of data analysis interpretation. Students learn how data collection, data analysis, and results are interconnected and interdependent. Another goal of the course is to show that the quality of an ecological scientific publication strongly depends on feedback that helps the researcher adopt and improve his or her preliminary investigation plan and also develops her or his capacity to fruitfully collaborate with other colleagues.

The teaching staff accompanied the students along a transect passing through four different types of forest stations. The transect was relatively small (length < 1 km; width: 200 m) and could be considered climatically homogeneous. The group stopped at each forest station, making observations and measurements of the vegetation and soil with the goal to be able to answer the following fundamental questions:

- Are there main ecological factors that can explain the observed subdivisions in forest stations?
- What are the differences at the level of soil and vegetation biodiversity and how is it possible to investigate and present these differences?
- Are soil and vegetation interdependent?
- Is it possible to predict the evolution of these systems in response to processes of climatic global warming?

The students were divided into 4 groups, each of them collecting data from a single station. The data was then shared at the end of the second day with the other groups for statistical analysis. Each group prepared their own statistical analysis and report. This article is based on the report presented by Tanguy F., Jouhanique T. and Terrigeol A., translated in English by Indorf M.-F. The other students made a similar report and proofread this one which had a clearer structure. The corresponding author coordinated the redaction of this paper and realised the photographic report.

2. Introduction

Understanding of the soil functioning is crucial, especially in considering agricultural needs and climate regulation. Exchanges are made between air, water, and living organisms but we still don’t understand all the processes involved. These compartments are not isolated as numerous interactions occur between the soil, the flora, and the fauna.

Soil micro-organisms like bacteria and archaea are important actors in this process. They have the ability to digest all the organic compounds in the soil, even the humic or phenolic ones such as tannins (Lavelle et al., 1995a; Barot et al., 2007; Clause et al., 2014; Dickson and Broyer, 1972; Lavelle, 2009). However, their activity remains limited without the macro-organisms which modify the environment in time and space (Lavelle et al., 1995b).

Plants, for their part can influence soil properties by producing chemicals and organic compounds affecting litter, humus, and soil (Van der Putten et al., 2013; Ponge et al., 2014, 2011, 1997).

The goal of this study is to demonstrate how pedogenesis soil formation under the same climate can vary within short distances due to different geological subsoil structures, and how this drives the entire ecosystem, from soil organisms to plant cover.

3. Materials and methods

3.1. The Butte Montceau

The Butte Montceau (N48°24′34″, E2°44′37″) is a 125 m high hill located east of Fontainebleau along the Seine River. The Butte is made of several geological strata dating mainly from the Oligocene. The Sannoisian limestone form the first marine deposit, followed by the Brie Limestone (10–15 m thick). The 40 m thick stratum of sand forms the most imposing part of the Butte and dates back to the Stampilian Stage. The Butte is mainly covered by forest vegetation. The different study stations are characterised by their soil, exposition, and floristic composition (Fig. 1).

The Butte Montceau, along with other similar rises just south of the town of Avon, is quite remarkable as it stands apart from the initial sedimentary stratum (the Beauce limestone) that can be found further south, stretching from the town of Étampes to the Cher Valley. In this region, the initial sedimentary stratum is usually 40 m thick.

3.2. Sampling design

We studied four contrasted stations along a 500 m transect. Each station hosted a different subsoil structure and exposure. As mentioned above, they are all located on the Butte Montceau and identified in Fig. 1 by their number. Station 1 corresponds to summit, and station 4 is next to the Seine River.

Flora and fauna: Five square patches of 100 m2 were laid out at each station and these were used as replicates for floristic inventories and soil and litter samples. The patches were aligned along a transect that was perpendicular to the slope, so that all replicates were at the same altitude. A distance of 10 m was respected between each patch corresponding to the width of a patch. The five patches provided a prospection zone large enough for the floristic inventory.

A quadrat of 50 cm x 50 cm was placed in the centre of each patch (Fig. 2a, b, c). All litter (approximately OL + OF horizons), inside the quadrats was then collected into a sack, weighed and identified for each tree species. White rot was evaluated for each species on a basis of a 10-leaf sample for each species.

Soil properties: a soil chunk (soil without "litter", i.e. soil without OL and OF horizons) of about 1000 cm³ (10 × 10 × 10) was then carefully extracted from each quadrat, in order to preserve at best, the different horizons for future chemical analyses. This chuck corresponded mainly to the A horizon in stations 1, 3 and 4, and to (OH
3.3. Methods

3.3.1. Humus and soil profile

Due to varying soil depths at each station, a soil auger was sometimes used to analyse subsoils beyond 60 cm deep, and at other times, a pit of 30 cm was sufficient. The different horizons were laid out on a flat surface in order to facilitate observations (Figs. 4–7).

Names and codes of diagnostic horizons and soil correspond to Référentiel Pédologique (AFES, 2009) and IUSS Working Group WRB (2015) references; for the ones of humus systems and forms we followed Humusica 1 (Horizons: article 4, and classification: article 5).

Each horizon was then characterised by its thickness, colour, texture, pH, and the presence of carbonate compounds. Various tools were used such as a tape measure, field pH metre, Munsell soil colour chart and a solution of hydrochloric acid (HCl) to determine the presence of carbonates.

The leaves of the litter horizon (OL) were separated by species origin and then weighed so as to know the percentages for each species in the litter make-up.

3.3.2. Soil physical and chemical measures

The following physical and chemical measures were effectuated in the lab on the soil chunks taken from each station. The presence of carbonates was determined by adding a small quantity of dilute HCl directly onto the horizon. The presence or absence of effervescence showed the presence or absence of carbonates.

3.3.2.1. pH measurements. For field pH, several grams of soil were collected from each horizon, to which a solution was added. The resulting colour was compared to the pH scale to identify an approximate pH of that horizon.

The method used was a pH 1:5 soil: water suspension. Five mixed grams of soil were taken from each soil chunk and placed in a glass jar. A five-fold dilution was created by adding 25 mL of distilled water to the 5 g of soil. The mixture was then agitated on a shaker table for 30 min before being left to rest for 1 h. A calibrated pH meter was used to measure the pH of the supernatant.

3.3.2.2. Residual water content measurements. The residual water content (RH) refers to the percentage of water contained in the soil. This factor makes it possible to convert concentrations for fresh soil into concentrations for dry soil.

Five grams of soil were collected in an aluminium weighing tin and kept overnight in an oven set at 105 °C. Upon removal, the tin was left to cool in a desiccator, before being weighed.

The residual water content was calculated as follows:

$$\text{RH} = \frac{(\text{mass of fresh soil} - \text{mass of dry soil})}{\text{mass of fresh soil}}$$

3.3.2.3. Nitrogen concentration measurements. Knowing the mineral nitrogen composition of a soil allows for a better understanding of the local ecosystem functioning, while also taking into consideration the results from the floristic inventory, the litter, and the soil fauna inventory. The first step was the extraction of all ions present in the soil, including those aggregated with fine particles. A 1 M KCl solution served as an extraction buffer, because of its high ionic strength and stability during the different preparatory stages. To avoid saturation of the extraction by the KCl, the 1:5 ratio was respected between soil mass: volume. Saturation would cause the KCl to become a limiting reagent, and thus interfere with the extraction of all ions.

Ten grams of soil were taken from the soil chunk, and 50 mL of KCl added. The mixture was homogenised before being set on a shaker table for 45 min. The prepared sample was then filtered (medium wide pore size) and the filtrate collected in a glass jar. The 3 forms of mineral nitrogen were then determined individually.

The method of determination of Nitrates was done in two steps. The nitrates were first reduced into nitrates by cadmium ions (Cd2+). These nitrates could then be determined by using a variant of the Griess method. When sulphanilic acid is added, nitrite ions form a diazonium salt. This salt then reacts with an amine, α-Naphthylamine, and forms an azo dye that absorbs at 525 nm. Zeroing of the spectrophotometer was done with 6 mL of pure filtrate. A small amount of nitrate reagent (HI 93728-0) was added to the tube then shaken vigorously for 10 s, followed by 50 s of less intense mixing. After this, the tube was left alone
for 4’30 in order that the particles might be able to sediment before measuring absorbance (Fig. 8). The measure given is the concentration of nitrogen in the nitrate compound [N-NO3-]. In order to have the concentration of the nitrates, a simple conversion must be done based on the relation between the different molecular masses \([M(NO_3^-)/M(N-NO_3^-)]\).

The method used for the determination of Nitrites is adapted from a method used by the Environmental Protection Agency of the United States (EPA). The nitrite ions created with this technique produce a purple-coloured compound that absorbs at 525 nm. Zeroing was once again done, but with 10 mL of the pure filtrate. A small amount of reagent, Nitrite LR reagent (HI 93707-0) was added, and the solution was mixed for 15 s. This time, the spectrophotometer measured directly the concentration of nitrates.

For the Ammonium test, a variant of a method developed by the American Society for Testing and Materials (ATSM) was used. This technique is based on the Nessler method. The Nessler reagent decomposes when in the presence of ammonium ions, and produces di-mercury diiodide. This compound can be used in colorimetry to determine the concentration of ammonium ions. The Nessler reagent is obtained by adding two solutions to the filtrate. First, lye or sodium hydroxide (NaOH) is added, otherwise called solution A, followed by a second solution B containing anhydrous potassium iodide (KI) and
mercury iodide (HGI2). The absorbance can be measured at 420 nm. Zeroing was done with 10 mL of filtrate in a tube. 200 μL of solution A was added and mixed, then 200 μL of solution B was added and mixed. The spectrophotometric reading is given after a few seconds. This measurement corresponds to the concentration of nitrogen in the ammonium compound [N-NH4 + ].

3.3.3. Litter and soil fauna inventory
The fauna in the litter was manually collected in each sample taken from all stations. A classification based on main functional groups was also produced. However, in two cases, only a portion of the sample was used. The results were then extrapolated to the total litter mass.

Two techniques were used for collecting the soil fauna: manual sorting and Berlese-Tullgren funnel (Fig. 9a, b, c, d, e, f, g). Each time, 500 g was taken from the soil chunk, and all the litter content (0.25 m2) was observed.

3.3.4. Floristic inventory
The floristic diversity was evaluated based on the phytosociological sampling method using the minimal area and the Braun-Blanquet abundance-coverage indices (Fig. 10a). The plot size is defined as “the minimal surface which has as a rule to be occupied by a sample of a plant community if the normal specific assemblage will be able to develop.” (Westhoff and Van Der Maarel, 1978). Coverage quantifies the surface that a plant occupies inside a given plot.

The analysis of the plot must be carried out on a plot larger or equal to the minimal area. This is done so that the analysed surface best represents the combination of characteristic species. For example, a plot size of 400 m2 is usually considered representative of a woodland, with a woodland having certain species that characterise its structure.

- herbaceous stratum: plants less than 1 m;
- shrub stratum: plants between 1 m and 7 m;
- tree stratum: plants more than 7 m.

For each stratum, each species was classified (Fig. 10b) and assigned an abundance-coverage coefficient (Braun-Blanquet et al., 1952) which can be converted into a mean coverage percentage (Table 1). This is done to facilitate statistical analyses.

Table 1 Correspondences between Braun-Blanquet coefficients and coverage percentage.

4. Statistical analyses
ANOVA tests were used to compare stations’ fauna, flora and chemical composition. However, if the variances were unbalanced, tests on means were also conducted. The threshold for the significance level was set at 0.05.

Species diversity was calculated according to the Shannon Index, with S being the total number of species, n the number of individuals of species i, and N the total number of individuals.

All statistical analyses were performed using the R software. 3.2.2 (R Core Team, 2015).

5. Results
5.1. Forest stations
The observed soil at station 1 is a Calcisol (AFES, 2009) and Cambic Calcisol (IUSS Working Group WRB, 2015); with a Mull system and a Mesomull humus form (Humusica 1, article 5)(Fig. 4).

There are no coarse calcareous fragments in the A, nor the S horizons. The adsorbent complex is almost or completely saturated (S/CEC > 80%) with Ca2+. The C horizon is a mixture of silt and Fontainebleau sand with a sandy-loam texture. This is indicative of
Fig. 9. Berlese-Tullgren funnels and samples of collected soil animals: a) Soil is placed in each funnel and lamps are lighted. Animals escape downwards until arriving in a little jar placed under the funnel; b) small animals are placed in Petri dishes and observed under the microscope: white enchytraeids, spiders, insect larva in the centre and at the low edge, black Staphylinidae on the left, two large centipede yellow and stained, a small gamasid in the centre; c) centipede at the top, a group of white collemboletans, an earthworm egg and very small Oribatid acarid aside a pseudo-scorpion; d) Gamasida acarids; e) Oribatida acarids; f) a springtail on the moon; g) students in laboratory during the third day of training. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
chloric acid. The numerous rock fragments present in the soil pro-
leaching from the upper horizons (CaCO₃ deposits) as the silt is found
further down in the soil after being carried downward by water. This
leaching is prevalent. Under the BT is a C/R horizon composed of blocks
of limestone and clays. The pH is neutral. The bedrock is mainly
composed of Brie limestone.

The soil at station 2 is a Podzosol AFES (= Podzols, IUSS) is an older Luvisol (same name AFES and IUSS) with both E (II E) and BT (= Bt IUSS) horizons. The eluvial E horizon is depleted in clay, while the BT (= Bt IUSS) horizon is enriched in clay. Found at a depth of 120 cm, the BT horizon is not visible in Fig. 5.

The soil at station 3 is classified as a Luvisol (same name AFES and IUSS) with a Mull humus system and an Oligomull humus form (Humusica 1, article 5), (Fig. 6).

The substratum’s first part is composed of Fontainebleau sands. The organic horizon contains an OLn, pockets of OLv, and a scarce quantity of O. There is no OH horizon, and the humus form is an Oligomull. The organo-mineral A horizon (Ah, AFES, 2009; FAO, 2006; corresponding to a biomesostructured meA, Humusica 1, article 4) is rather acidic with a pHₜₜₜwater of 4–5. This acidity is unusual in Mull systems and most likely a punctual event due to very recent climatic conditions and the increase of acidophilous species. The leached horizon E is beige-coloured and has a low clay content due to eluviation or leaching. The pH is slightly acidic (5–6). The argic horizon BT is ochre-coloured and has a pH identical to that of E (5–6). The soil is active as plant litter is rapidly transformed due to microorganisms and earthworms. Nonetheless, there are not enough earthworms to combine clay and organic matter in a clay-humus complex. The biomesostructured A horizon is made of large aggregates (> 4 mm) characterised by a very weak structure (they easily break under low pressure between fingers). As a result, leaching is prevalent. Under the BT is a C/R horizon composed of blocks of limestone and clays. The pH is neutral. The bedrock is mainly composed of Brie limestone.

The soil at station 4 is a Calcosol (AFES, 2009) = Haplic Calcisol (IUSS, 2015) with a humus Mull and a Mesomull form (Humusica 1, art.
5), (Fig. 7).

The organic horizon is made up of a continuous OLn, while the OF and OH horizons are absent. This corresponds to a Mesomul (OL continuous) or almost an Eumull (OL discontinuous or absent). The organo-mineral horizon is an effervescent to HCl, calcareous (Aca, AFES, 2009 or Ahk, FAO, 2006). It has a lumpy structure because of the earthworms. Its pH is between 7 and 8. The structural horizon is cal-
carie (Sca = Bk), with a gradual transition into the A horizon. The structure is polyhedral. There are no visible carbonate aggregates from sedimentary rock formations in the A horizon, but some are present in the S horizon. In this kind of soil, the absorbing complex is saturated (S/ CEC > 95%), mainly by Ca²⁺. The Aca (Ahk) and Sca (Bk) horizons show effervescence with hydrochloric acid. The underlying C horizon is not visible, but is composed of altered limestone bedrock. This bedrock is called Champigny Limestone.

5.2. Physical and chemical measures of horizon a

The water content, pH, and nitrate, nitrite and ammonia levels for each station are shown in Fig. 11 (as well as in Table 2 of the Appen-
dices). Stations 2 and 3 present an acidic pH (< 5), distinctly different from the 2 others stations which present a neutral pH (7). The nitrate
A. Terrigeol et al.

5.4. Litter and soil fauna inventory

Fifty-one taxonomical groups were identified, taking into account distinctions between adult and larval stages. Taxonomical groups are generally identified to the Family, but in certain cases only to the Order or Super-Family (Appendices, Table 3). Almost 2000 individuals were identified from all stations, using various resources (Moreau, 1990; Leraut et al., 2003; Chinery, 2005). A Shannon diversity index was calculated for each replicate. Adults and larvae of the same taxonomical group were combined. The calculated indices are shown in the upper part of Fig. 15. Mean Shannon diversity indices are not significantly different in each station for litter nor for soil (ANOVA, p-value = 0.98 and 0.26 respectively). This is due to the important variability between replicates. However, the stations 2 and 3 exhibit higher average values compared to the stations 1 and 4. More replicates would then be needed in order to strengthen the statistical test.

The number of individuals collected in soil samples is about 10 times lower than that of the litter (lower part of Fig. 15). Similarly, diversity indices for soil samples are about half of those calculated for the litter samples.

The diversity index calculated for the litter is slightly correlated with pH (Figure 16 Figs. 16, 17). Two groups are observed, the first one, on the left correspond to the station 2 and 3, while station 1 and 4 are on the right. Differences between these two groups are significant (p-value < 0.05) with a stronger faunal diversity at lower pH.

Taxonomical groups have been attached to one or more of the seven ecological functions proposed by Lavelle (1996) (Appendices, Table 3). For the litter, half of the functions are predator functions, and predation occurs at all different levels (macrofauna, mesofauna, and microfauna). The function of the litter transformer represents about a third of the total for the stations 1 to 3 and one fourth for the station 4 (Mesomull). The difference is, however, not significant (ANOVA, p-value = 0.56).

On average, the ecosystem engineer function is better represented at the stations 1 and 4 than at 2 and 3. But once again, the difference is not significant (ANOVA, p-value = 0.6). In the soil, the ecosystem engineers are more prevalent in station 4 than in stations 1 and 2. The observed difference between averages is significant (ANOVA, p-value = 0.015). Litter transformers are just as well present in the soil sampling. However, we found many litter transformers (compared to the observed numbers) in the soil too. The differences on the observed averages for the litter transformers are not significant (ANOVA, p-value = 0.09).
At all 4 stations, 65 plant species were inventoried. The species list is presented in Table 4 of the Appendices. 13 species are listed in the tree stratum, 12 in the shrub stratum, and 40 in the herbaceous stratum.

From a floristic point of view, the 4 stations show some very differing characteristics.

Station 1 is an Oak forest, made up of pubescent oak trees. The southern exposure promotes the growth of sub-Mediterranean species in the northernmost limit of their range (Quercus pubescens, Carex humilis). Other species found in the tree and shrub strata are Fagus sylvatica, Sorbus latifolia, Crataegus monogyna, and Ligustrum vulgare. In the herbaceous stratum the dominant species are Brachypodium pinnatum, Euphorbia amygdaloides, Euphorbia cyparissias, and Teucrium chamaedrys.

Station 2 is an oak-beech forest (Quercus petraea, Fagus sylvatica) that has associated acidophilous species such as Pteridium aquilinum and Carex pilulifera. The herbaceous stratum is underdeveloped.

Station 3 is an Oak-hornbeam-beech forest (Quercus petraea, Carpinus betulus, Fagus sylvatica). Anemone nemorosa is largely represented in the herbaceous stratum as well as Lonicera periclymenum. A few acidophilous species are present (Pteridium aquilinum, Deschampsia flexuosa, Teucrium scorodonio).

Station 4 is also an Oak forest, but this time containing linden, maple, and European hornbeam (Quercus robur, Tilia platyphyllos, Acer pseudoplatanus, Carpinus betulus). The species-rich herbaceous stratum contains Mercurialis perennis, Lamium galeobdolon, Oranthogalum pyrenaicum, Ribes rubrum, Veronica officinalis, etc.

A Shannon index has been calculated on all replicates, using the Braun-Blanquet abundance-dominance coefficients. Species labelled with a ‘ + ’ or an ‘ † ’ are given a coefficient of 0.2 or 0.1 respectively. The calculated indices are given in Figure 16. The diversity in the tree stratum is not significantly different between stations (ANOVA test on the mean values of stations 1 and 2, p-value of 0.25 and 0.64 respectively).

However, for the shrub stratum, station 2 differs from the stations 1 and 4 with a lower level of diversity (test on mean, p-value of 0.016 and 0.022 respectively). This difference is also observed for the herbaceous stratum between the stations 1 and 2, but not between the stations 2 and 4 (test on mean, p-value of 0.016 and 0.11 respectively). For this same stratum, station 3 shows a lower mean diversity than the stations 1 and 4, but the difference is not significant. More replicates are needed to be more conclusive (test on mean, p-value of 0.07 and 0.26 respectively).

The diversity indices, calculated for the shrub and herbaceous strata, show a slight correlation with the soil pH (Figure 16). First, we observed a higher diversity for the herbaceous stratum compared to the shrub stratum. Secondly, the diversity seems to increase with the pH. Thirdly, no correlation was found for the tree stratum; the diversity was similar across all stations. Two groups were observed, one close to pH 4, which corresponds to stations 2 and 3 and the other one close to pH 5.
close to pH 7 corresponding to stations 1 and 4. Differences between those two groups are not significant, neither for the herbaceous stratum nor the shrub stratum.

6. Discussion

Each of the four stations that were analysed in this study differ in their soil profile, the physical and chemical properties and the characteristics of the litter (OL + OF horizons), the first 10 cm of “soil without litter” (OH, A, B horizons), the soil fauna and the vegetation. Some differences were higher between some stations, depending on soil and humus systems. Two different groups were observed according to their pH values. However, stations 1 and 4, which have similar Shannon indexes and pH of the basic topsoil A horizons, were separated from the stations 2 and 3, which show different topsoil horizons, respectively acid A and (OH + A + B) horizons. In other words, pH seems to play an important role on the faunal and floral diversity. There is a relationship between pH and humus/soil systems as shown in the literature (Toutain, 1981; AFES, 2009; Zanella et al., 2011a, 2011b). Furthermore, the humus/soil system influences the vegetation (Ponge, 1999, 2003; Bigelow and Canham, 2002), and the optimum soil pH for each plant formation corresponds to what was found during our study. Along the Fontainebleau transect the change in pH in the first 10 cm of soil (under OL and OF horizons, Figs. 4–7), is particularly important, as very few plant individuals were found at pH levels between 5.0 and 6.5. The pH gradient along the transect (station 1, A horizon: pH about 7, station 2 (OH + A + B horizons) and 3 (A horizon); pH near 5, station 4, A horizon: pH 7) leads to several hypotheses, which will need further investigation for validation. It is possible that a) the high filtering capacity of the Fontainebleau sands could easily lose its content in bases through leaching; b) the light slope of the Fontainebleau sand layer does not allow for the accumulation of large calcareous colluviums covering this acid sand layer and the abrupt physical passage from calcareous to acid stations is the only one present in the area; c) over time the forest management of the beech forest growing on Podzol and Luvisol promotes an even-aged stand, which may have facilitated lixiviation (Luvisol genesis) and podzolisation (Podzol genesis) of the filtering substratum, especially under the mature adult stands (as observed), where the shrub stratum is systematically cleared away by managerial interventions.

Another interesting fact is the higher faunal diversity for low soil pH (around 4) while the floral diversity seems to be higher with a higher pH value (around 7). The pH may not be the only factor explaining this change in diversity, however it must play an important role. We did not measure the average weight of soil and litter fauna per gram, however the diversity may already be a good indicator. It has already been shown that the humus systems (Mull or Moder) could have some consequences on faunal diversity, with a higher diversity in the Mull soil (Schaefer and Schauermann, 1990; Zanella et al., 2011a; Humusica 1, articles 4 and 8 and Humusica 8, 2017). However, because of the low number of species observed, it is impossible to draw any firm conclusions. Indeed, soil and litter fauna, with their degradation process, can change the soil reference. Faunal faeces, for example, can increase the pH, stimulate biological activity and increase the humification process (Bachelier, 1978; Toutain, 1981; Zanella et al., 2011b).

Furthermore, it has been shown that plant diversity can have important consequences on faunal diversity (Ponge, 1999, 2003, 2013; Meier and Bowman, 2008; Wardle, 2006). Thus, faunal diversity can also change soil properties and influence floral diversity and vice-versa.

Station 1: the soil is calcareous with a neutral pH. It is relatively dry, and as a consequence, there are few earthworms. Nonetheless, the litter is classified as Mesomull as it is efficiently degraded. Few fungus species
participate in this transformation as is noted by a lack of white rot. Arthropods are thus largely implicated in the transformation processes. The large species diversity of the herbaceous and shrub strata is largely favoured by the southern exposure. The tree stratum is much less developed in comparison to the other stations.

Station 2: the soil, which is very acid, is situated on a sandy subsoil, with a very low humidity and few earthworms. The clay-humus complex is fairly absent and thus the cations are not retained. The resulting soil is not very rich. The topsoil, classified as Dysmoder, is transformed mainly by arthropods, but also by a few fungi. The slow transformation leaves behind large quantities of decaying and partially decayed organic matter, which in turn allows for a large diversity of arthropods involved in each step of the transformation process (the significance remains to be determined statistically).

The vegetation is limited by the edaphic conditions which favour acidophil plants. Thereby the herbaceous and brush strata are not very diverse.

Station 3: the acid soil is also positioned on a sandy subsoil, but is more humid than the previous stations, and thus has a more active humus. However, there are not enough earthworms to create a clay-humus complex. The litter at the top of an Oligomull, is efficiently degraded by arthropods, but also by some earthworms and some fungi. The pedofauna diversity is rather important, but this needs to be confirmed statistically.

The edaphic conditions are less restricting than for the station 2, which allows for a few more plant species to survive. The Shannon diversity index rises slightly for the shrub and tree strata, but once again this has yet to be confirmed statistically.

In Fontainebleau forest, the process of podzolisation has been well investigated (Robin, 1968, 1979, 1990, 1993, 2005; Robin et al., 1983; review in Humusica 3, Delaporte et al.: Structural and functional differences in the belowground compartment of healthy and declining beech trees) and our Luvisols and Podzols perfectly fits the descriptions of soil profiles studied in Robin’s articles. In Fontainebleau beech-oak forests, on sandy substrate (as in stations 1, 2 and 3), the soil fertility is strongly related to the accessibility of Calcium ions. Stations 1, 2 and 3 are placed on Fontainebleau sand between Beauce and Brie limestone layers (Fig. 1):
a) at the top, the Beaune limestone covering as a cap the Montceau Butte, may feed the Calcisol of station 1. Applying hydrochloric acid along the soil profile causes effervescence only at the bottom. A process of lixiviation removes the free CaCO₃ dissolved in water, which after losing its water may precipitate near the bottom;

b) Beaune limestone transported by gravity water can also feed the station 2 (on the same sand, in a lower position than station 1) on the condition of having an impermeable substratum that would prevent water from leaving the system. In station 2, we found the top of a BT (horizon with clay accumulation) from an ancient Luvisol at a depth of 120 cm. The pH corresponding to this deep BT horizon was about 6. This may explain the relative fertility of this Fago-Quercetum forest (adult beech and oak trees reaching a height of 25–30 m) even if characterised by acidic humus system and soil;

c) at the bottom, the Brie limestone may furnish Calcium to the forest system of station 3, assuming that this spot be characterised by a Luvisol with a BT horizon that is not compact nor to thick. In some areas of the station 3, the limestone was near to the surface (< 60 cm), hindering deeper prospection in the soil and reducing the volume of exploitable soil by roots. We believe that station 3 attained a nearly neutral soil over time which can support a richer biodiversity as our measurements proved.

The combination of the thickness and quality (more or less enriched in silt or clay) of the Fontainebleau sands, the strength of the lixiviation processes, and the clay eluviation or podzolisation influencing nutrient availability for sustained forest ecosystems, can explain the variability in conditions we found in stations 1, 2 and 3. Even though different, stations 2 and 3 were more similar when compared to the calcic station 1, which tends to react similarly as the more calcareous station 4.

Station 4: the calcic soil has a pH of 7, corresponding to neutral. The humidity is important and the humus is active. The earthworms help in the processes, and the clay eluviation or podzolisation influencing nutrient availability for sustained forest ecosystems, can explain the variability in conditions we found in stations 1, 2 and 3. Even though different, stations 2 and 3 were more similar when compared to the calcic station 1, which tends to react similarly as the more calcareous station 4. The favourable soil conditions here allow for a species-rich vegetation equal to that of the first station; this applies to each stratum. This is surprising with regards to its north-eastern exposure, which is less favourable than the first station’s south-western exposure. However, this can be explained by the close proximity of water, which can especially be beneficial during hot summers.

7. Conclusion

Various types of soils and the corresponding pedogenesis processes were studied in this exercise. This study alsoanalysed the relationship between soils’ physical and chemical properties, the litter and soil fauna, and the corresponding vegetation. Interesting relations between soil properties and floral and faunal diversity have been shown. In only a 500 m gradient, under the same climate conditions, it is very interesting to note such differences among soil profiles.

The variability in the results between replicates sometimes skewed the statistical analyses and occasionally limited the possibility to define trends. To counteract this problem, it will be necessary to do more replicates and have a better control of the experimental biases.

The litter and soil fauna densities per square metre cited in the literature did not correspond to our results, but this is most likely due to the methodology used. A lot more individuals were found in the stations 1 and 4 than in the stations 3 and 4. It was also not possible for us to identify the micro-invertebrates. Molecular tools and techniques such as DNA barcoding would greatly help in being more precise.

Regarding the recent climatic trend, litter decomposition could be influenced by hygrometry and temperature could also have important consequences on the biodiversity of the Butte Montceau, especially if management interventions are inadequate.

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