The soils of natural environments for growth of truffles in Italy

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Received 18 January 2005 / Accepted 8 April 2005

Abstract. Results from all studies on soils where the main edible truffles occur naturally are assessed. For *Tuber melanosporum* soils, the main physical and chemical characteristics have been established in the field and in the laboratory. They are always well-aired and have an optimal particle aggregation, good water-drainage, the constant presence of a limestone skeleton, parent material composed of limestone detritus or intensely fractured limestone rocks. Their pH_{H_2O}, pH_{KCl}, organic carbon, and EDTA extractable Mn are fundamental parameters to define the suitability of a soil for this species. For *T. magnatum,* research to date has not been able to determine the main pedological parameters, but has managed to characterize parent material and geomorphological dynamics which lead to the formation of soils suitable for this truffle. Those soils are well-drained and show a great number of pores, with a bulk density always around 1 and constant humidity. For *T. aestivum,* research has been inconclusive because results have been so variable. That variability can be correlated with a strong genetic variability in this species which, in its several forms, has adapted itself to many soil environments. Not much is known about soil characteristics for *T. brumale,* except that it prefers soils much more humid than those of other truffles; water stagnation is frequent and EDTA extractable Mn is always much higher. Nearly nothing is known about *T. borchii.*

Key words: Italy, soil characteristics, truffle natural environment of growth, *Tuber*

Introduction

Almost all edible truffle species occur in Italy, but biologists and ecologists have concentrated especially on the more economically significant species: *Tuber magnatum* Pico (the famous white truffle) and *T. melanosporum* Vittad. (the famous black truffle) for their very high unit price, and *T. aestivum* Vittad. (the scorzone or summer truffle) for its great abundance. Other species have received little attention: *T. brumale* Vittad. and *T. borchii* Vittad. because of their very low economic value, and *T. uncinatum* Chatin because of its low abundance at a national level and its low concentrations at a local level – this species is in any case often not distinguished from *T. aestivum* by truffle-hunters who generally refer only to “scorzone” and only sometimes to “summer scorzone” (*T. aestivum*) and “winter scorzone” (*T. uncinatum*). For such reasons, especially concerning soils, significant information is only available for those most studied truffles, while for the others information is rare, insufficient and often incomplete.

Materials and Methods

This study of truffle-bed soils comprised two phases: the first on-site and the second in the laboratory. The on-site work included botanical and morphological descriptions, an examination of the soil profile (Sanesi 1977) and samples of the horizons of pedons representative of each environmental condition. Physico-chemical analyses, aimed at characterizing and classifying the soils, were carried out in the laboratory using samples collected in accordance with official methods for chemical analysis of soils (Metodi Ufficiali di Analisi Chimica del Suolo 1992). In

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detail: silt and clay grain-size distribution was determined by the pipette method, and the sandy fraction by wet sieving; determination of total limestone by the Dietrich-Fruehling calcimeter and percentage of Organic Carbon by the Walkley and Black method. Heavy metal content (Fe, Mn, Cu, Zn) was assessed with an Atomic Absorption Spectrophotometer after extraction with ammonium acetate 0.5 M solution + plugged EDTA with pH 4.65. The soil reaction was given in water and in a solution 1N of KCl, with a soil/solution report/ratio of 1:2.5 (weight/volume).

Results

Soils of Tuber melanosporum

Severe erosion, especially laminar erosion, strongly affecting vertical development of the soil profile, was observed in all the sites. The soils appeared to be truncated, i.e. missing of part of the higher horizons, or to be in the early phases of evolution. Almost always the pianelli had the aspect of a true "heap of stones", with a surface made of a homogeneous and continuous skeleton. The stony coat, almost pure by selective removal of the fine earth, protects the soil below against further erosion and contributes to maintenance of a certain level of moisture in the soil by limiting the capillary rise of water and successive evaporation. Soil horizons where carpophores were found always had a good structure; the fine and average aggregates of granular type dominated and those of a fine subangular blocky type were not unusual. The latter were easily crumbled in granular aggregates if they were slightly developed, or in very fine polyhedrons if the degree of structuring was more expressed. Even if the presence of a skeleton was dominant (> 80 %), the fine earth never appeared compact, but it always had a good organization and was always very friable. The whole of such configurations constantly presented characteristics of great friability in the soil, in spite of the high contents in rock fragments.

The permeability, drainage and ventilation seemed to reflect conditions of aggregation; they were always very good and pedological features indicating even temporary water saturation were never found. Another characteristic common on the soils studied was the absence of surface cracking even during time of extreme dryness. The soil skeleton, in percentage and dimensions which varied between different places, was always angular or with slightly broken edges, and not very faded. From a taxonomic point of view, the studied soils belong, according to the classification suggested by USDA (Soil Survey Staff 1997), particularly to the Order of Inceptisols, and in second place to the Entisols and Mollisols; according to the classification suggested by the WRB (Deckers *et al.* 1998) to Cambisols and in sub-order to Calcisols and Regosols. In general a weak differentiation of the profile was observed, because the soil was in the first phases of evolution, or because of the beginning of formation of a thin organic epipedon on horizons of older pedogenesis soils more altered below. In all the cases the soil environments were subject to intense erosion which, in the first place, completely exposed the substratum, and secondly truncated the original soil sequence. In these last situations a rejuvenated profile was often observed due to arrival on the surface of calcareous material coming from the slopes above. The soils which were observed, defined according to Soil Survey Staff and WRB respectively, are summarized in more detail in Table 1.

Table 1. The soils of *Tuber melanosporum* in Italy

WRB 1998 Classification	Soil Taxonomy 1997 Classification
Calcaric Regosols	Typic Xerorthents
Calcari-Leptic Cambisols	Lithic Eutrochrepts
Calcaric Cambisols Chromi-Calcaric Cambisols	Typic Xerochrepts
Calcari-Mollic Cambisols	Eutrochreptic Rendolls
Calcari-Fluvic Cambisols	Udifluventic Ustochrepts
Hypercalcic Calcisols Hypercalci-Skeletic Calcisols	Calcixerollic Xerochrepts

Such pedological typologies represent much of what can be found in calcareous sediments; this suggests that most zones with carbonatic rocks are suitable for production of *T. melanosporum.* In reality, natural truffle sites are distributed in a punctiform way and not often present in soils classified like those mentioned, even in comparable conditions of climate, morphology and vegetation. This suggests that, apart from parameters which contribute to soil classification, other characteristics also define the aptitude of a given soil for producing this truffle (De Simone *et al.* 1993; Lorenzoni *et al.* 1995; Raglione *et al.* 1997).

Using all possible on-site observations, all these soils present common properties which can be summarized in the following way:

- structure always well developed, primarily granular, but also of a fine subangular blocky type; sometimes, in deeper horizons, a medium subangular blocky type can be observed which is little developed and easily crumbling into smaller aggregates;
- absence of pedological figures like pseudogley, concretions, nodules or coatings of Fe and Mn related to a saturation by even temporary water;
- absence of clay and oxides coatings;
- absence of pedological figures like faces of pressure or slip suggestive of an accentuated dynamism of the structures;
- strong porosity especially among the aggregates which are furthermore always of friable consistence;
- strong aeration, excellent drainage and excellent permeability;
- persistent presence of a minimum of moisture; the soil is never completely dry.

The physico-chemical characteristics of the soils of *T. melanosporum,* show, as already reported in the bibliography (Delmas & Durand 1971; Bencivenga *et al.* 1988; Poitou 1988; Raglione *et al.* 1992, 2001), a strong variability within each parameter. These are illustrated in Table 2.

Table 2. Principal physico-chemical characteristics of the soils of *Tuber melanosporum*

Variable	Mean	Std. Dev.	Min.	Max.	V.C. (%)
Clay (%)	20.1	12.5	1.2	46.2	62.2
Silt (%)	51.4	16.6	4.9	83.3	32.4
Sand (%)	28.4	12.1	10.7	62.3	42.6
Texture Index	38.9	11.7	21.0	88.0	30.1
Structure Index	80.8	13.5	46.5	97.5	16.8
pH_{KCl}	7.3	0.1	7.1	7.7	1.8
pH_{H_2O}	7.9	0.2	7.5	8.4	2.4
$CaCO_3$ (%)	34.9	22.0	1.0	76.0	63.0
C (%)	3.2	1.9	0.6	9.8	59.2
Fe (mg/kg)	148.5	90.3	31.7	323.3	60.8
Mn (mg/kg)	237.7	132.5	53.3	534.1	55.7
Zn (mg/kg)	9.0	7.7	1.1	38.7	84.7
Cu (mg/kg)	17.9	17.8	1.1	88.9	99.4

It is obvious from analysis of Table 2 that some variables (in particular the pH, both in H_2O and in KCl, and the structure index) show a remarkable constancy of values, while the most others have high levels of variability. What precedes would seem to confirm what the cited authors have reported already about the low significance of most canonical analyses in defining characteristics of soils suitable for production of *T. melanosporum,* though the two values of soil reaction noted and the structure index appear interesting. The minimal values of 7.5 and 7.1, taken respectively by the pH_{H_2O} and the pH_{KCl} tests, indicate that soils which are characterized by values below the lower limits for those two parameters are unlikely to be suited for production of truffles.

Soils of Tuber aestivum

Tuber aestivum is without doubt the edible truffle most widespread in Italy. It develops in many environments, nearly everywhere where rocks which contain limestone emerge. *Tuber aestivum* tolerates both higher and lower temperatures, and climates both wetter and drier than *T. melanosporum. Tuber aestivum* "burns" the soil like *T. melanosporum,* but can also be found in forest truffle beds without "pianello". The soils of *T. aestivum* are also subjected to severe erosive action which strongly conditions vertical development of the profile, but their surface is less stony that of *T. melanosporum,* especially when truffle beds are located in woodland. Pedological typologies of *T. aestivum* are the same as those of *T. melanosporum,* but the climate of the soil can be wetter or drier. On-site observations show that soils of *T. aestivum* present common properties which can be summarized thus:

- structure always well developed, primarily granular in the most superficial layer, but of the medium subangular blocky type in the deeper horizons; the aggregates are more solid and crumble with more difficulty than those of *T. melanosporum;*
- pedological figures like pseudogley can be present;
- absence of clay and oxides coatings;
- absence of pedological figures as slip faces which indicate an accentuated dynamism of the structures, but pressure faces, which may not be very obvious, can be present;
- good porosity, especially among the aggregates;
- good aeration, good drainage, and strong permeability.

In summary, *T. aestivum* develops in a soil environment less aerated, less drained, and less soft than does *T. melanosporum.*

Physico-chemical characteristics of soils of *T. aestivum* also show, as already reported in the bibliography (Chevalier 1979; Gardin *et al.* 1997; Raglione *et al.* 2001), a strong variability inside each parameter. They are illustrated in Table 3.

There are not many differences from the situation with *T. melanosporum;* only the values of the pH_{KCl}, the pH_{H_2O}, Organic Carbon, and exchangeable Mn content are much more variable. Minimal values obtained by the pH_{KCl} and pH_{H_2O} tests are well below of those of *T. melanosporum. Tuber aestivum* can also live in soil environments without carbonates ($CaCO_3$ = 0) in the fine earth if the soil has a calcareous skeleton. The greater variability of soil environments where *T. aestivum* grows compared with those of *T. melanosporum* was confirmed by biogenetic studies on DNA of the two truffles, which showed a large genetic variability of *T. aestivum,* compared with a genetic constancy in *T. melanosporum.*

Soils of Tuber brumale

Tuber brumale is, for its particular musky taste, without doubt the least sought-after edible truffle. It develops in many environments, almost everywhere where one finds *T.*

Table 3. Principal physico-chemical characteristics of the soils of *Tuber aestivum*

Variable	Mean	Std. Dev	Min.	Max	V.C. (%)
Clay (%)	33.0	13.7	2.0	78.0	41.5
Silt (%)	42.0	12.1	7.0	78.0	28.8
Sand (%)	24.0	10.4	12.0	65.0	43.3
Structure Index	80.9	14.8	42.8	97.9	18.3
pH_{KCl}	7.0	0.5	4.9	7.4	7.1
pH_{H_2O}	7.8	0.4	6.3	8.5	5.1
$CaCO_3$ (%)	35.7	23.4	0.0	75.0	65.5
C (%)	3.4	3.6	0.3	16.0	105.9
Fe (mg/kg)	263.9	191.7	41.5	677.3	72.6
Mn (mg/kg)	267.0	495.7	72.9	2183.8	185.6
Zn (mg/kg)	12.1	6.1	4.8	22.2	50.4
Cu (mg/kg)	61.1	41.2	7.0	163.0	67.4

melanosporum and *T. magnatum. Tuber brumale* prefers soils wetter than those for other truffles. It does not "burn" the soil like *T. melanosporum.* The soils of *T. brumale* are not subject to erosion, but are always in the position of a morphological bottom, or where, in some way, there is accumulation of materials. Pedological typologies of *T. brumale* are the same as those of *T. magnatum,* but the pedoclimate is wetter. On-site observations show that soils of *T. brumale* present common properties which can be summarized thus:

- well developed, primarily medium subangular blocky type, in the surface layer, but moderately developed in the deeper horizons; the aggregates are more solid and crumbling with more difficulty than those of *T. melanosporum, T. aestivum,* and *T. magnatum;*
- pedological figures like pseudogley can be present;
- horizons with little or no structure (apedal) can be present;
- pressure faces indicating some dynamism of the structures can be present;
- moderate porosity;
- moderate aeration, moderate drainage and moderate permeability.

In summary, *T. brumale* grows in a soil environment less aired, less drained, less soft, more wet than that of other truffles. Physico-chemical characteristics of the soils of *T. brumale* show strong variability inside each parameter. These are illustrated in Table 4.

There are not many differences in comparison with *T. aestivum;* values of the pH_{KCl}, the pH_{H_2O}, and the exchangeable Mn content can, however, be very different from those of *T. melanosporum.*

Table 4. Principal physico-chemical characteristics of the soils of *Tuber brumale*

Variable	Mean	Std. Dev.	Min.	Max.	V.C. (%)
Clay (%)	32.0	9.2	1.0	49.0	28.7
Silt (%)	43.0	11.8	17.0	76.0	27.4
Sand (%)	25.0	8.6	11.0	53.0	34.4
Structure Index	84.8	12.4	70.7	94.3	14.6
pH_{KCl}	6.9	0.4	5.7	7.5	5.8
pH_{H_2O}	7.7	0.4	6.8	8.2	5.2
$CaCO_3$ (%)	34.1	26.6	0.0	80.6	78.0
C (%)	2.2	1.6	0.7	8.4	72.7
Fe (mg/kg)	264.1	193.9	64.5	772.4	73.4
Mn (mg/kg)	464.4	293.2	137.3	959.3	63.1
Zn (mg/kg)	8.2	6.1	2.7	21.6	74.4
Cu (mg/kg)	11.5	7.4	5.4	28.0	64.3

Soils of Tuber magnatum

While *T. melanosporum* grows in one geological environment only, *T. magnatum* can occure in many environments: alluvial deposits of rivers and streams, slopes of marine and lake sediments of the Pliocene and Quaternary subject to landslides, valley bottoms of marine and lake sediments of the Pliocene and Quaternary, slopes and valley bottoms of the hills and the mountains where soft marly rocks outcrop. In all these situations the $CaCO_3$ content and the morphological dynamism which causes disorganization of soil particles are encountered; the pedoclimate must be always wet. The great abundance of $CaCO_3$ (tender marly rocks) and disorganization of the particles give rise to a very porous soil, where bulk density is about 1. In the absence of morphological dynamism, evolution of the soil gives rise to a reorganization of the particles, with consequent reduction of much of the porosity. In such cases the soil environment becomes adverse to the development of truffles, and this leads to loss of production. For this reason, soils favourable for development of *T. magnatum* are generally not very advanced (entisols), but they can have a B cambic horizon (inceptisols) when the bed rock is a tender marly rock (Tab. 5).

Table 5. The soils of *Tuber magnatum* in Italy

Soil Taxonomy Classification 1997
Aquic Udorthents
Typic Udorthents
Typic Udifluvents
Typic Eutrochrepts
Aquic Eutrochrepts
Rendollic Eutrochrepts
Entic Hapludolls

On-site observations show that soils of *T. magnatum* present the following common properties:

- weakly developed structure, primarily granular or of the medium subangular blocky type, very weak or firm;
- pedological figures like the pseudogley can be present;
- horizons with little or no structure (apedal) can be present;
- pressure faces indicative of a dynamism of the structures can be present;
- very high porosity;
- very good aeration for the most part of the year.

Physico-chemical characteristics of the soils of *T. magnatum* show strong variability within each parameter. These are illustrated in Tables 6-9.

Analysis of Tables 6-9 shows that they do not contain the same variables, but that among those variables held in common there is not much difference. This suggests that in all environments the soils of *T. magnatum* have the same characteristics and that, unlike for *T. melanosporum,* it is not the geological environment which conditions development and characteristics of the soils, but geomorphological dynamics (Lulli & Primavera 2001).

Soils of Tuber uncinatum *and* T. borchii

There is very little information in Italy about the soils of *T. uncinatum* and *T. borchii,* because they have been little studied. *Tuber uncinatum* is generally associated with *T. aestivum* and both are called "scorzone" without distinction. From this one can say that they live the same soils, even if *T. uncinatum* prefers a pedoclimate wetter than *T. aestivum.*

Tuber borchii develops in soils which are very strongly drained; this condition occurs with the presence of a great quantity of sand or stones, or in morphological conditions of a topographic top.

Discussion

After analysis of pedological characteristics for natural truffle beds of *Tuber melanosporum, T. aestivum,* and *T. brumale,* it is possible to identify the most significant variables distinguishing the soils of these three species by using a Discriminating Analysis on three levels of classification (*T. melanosporum, T. aestivum,* and *T. brumale*). During information processing, using the whole data-set, the best discriminating result was obtained from the variables pH_{H_2O}, pH_{KCl}, organic C content and EDTA extractable Mn content. Results of the Discriminating Analysis are shown in Fig. 1.

Figure show that soil samples of the three truffle species are grouped in sufficiently distinct clusters. A greater uncertainty appears between the fields of groups 1 (*T. melanosporum*) and 3 (*T. brumale*) and those of group 2 (*T. aestivum*); that of group 2 appears more widespread.

Table 10 illustrates percentages of the correctly classified cases.

The results of classification show a clear capacity of Discriminating Analysis to assign samples of soils coming from truffle natural beds of *T. melanosporum* (91.7 % of the cases) to the correct group; in no case was there an erroneous allocation to the *T. aestivum* group, and in only 8.3 % case to the *T. brumale* group.

The situation for *T. brumale* is similar, with 75 % of the cases correctly ascribed, 25 % classified as pertaining to *T. aestivum,* and 0 % classified as pertaining to *T. melanosporum.*

For *T. aestivum,* however, results appear uncertain, with only the 55.6 % of cases correctly recognized and with an equal 22.2 % of assigned to each of *T. melanosporum* and *T. brumale.* This agrees with the geomorphological and pedological observations carried out on the ground about the greatest variability of the characteristics of the environments with the presence of *T. aestivum* compared to those where one can find *T. melanosporum* and *T. brumale.*

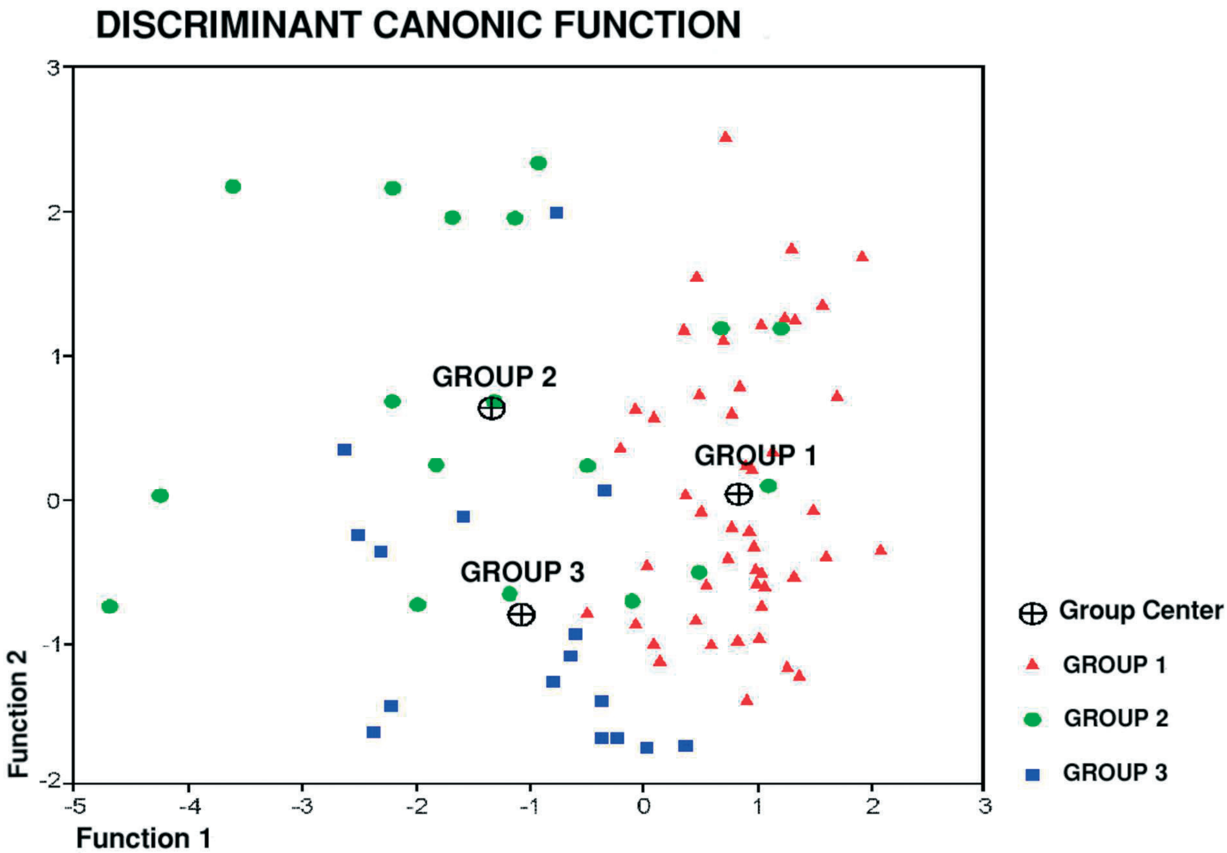

Fig. 1. Results of the Discriminating Analysis on three groups of soils. Group 1 = *Tuber melanosporum;* Group 2 = *T. aestivum;* Group 3 = *T. brumale.* The following variables were used: pH_{H_2O}, pH_{KCl}, C organic, EDTA extractable Mn

Table 6. Principal physico-chemical characteristics of the soils of *Tuber magnatum* on marly tender rocks

Variable	Mean	Std. Dev	Min.	Max.	V.C. (%)
Clay (%)	30.0	7.4	6.0	40.0	24.9
Silt (%)	54.0	8.1	38.0	85.0	15.1
Sand (%)	17.0	6.3	8.0	35.0	37.5
Texture Index	47.7	5.7	28.0	55.6	11.9
Structure Index	75.9	0.8	75.4	76.5	1.1
pH_{KCl}	7.1	0.1	6.9	7.6	1.4
pH_{H_2O}	8.0	0.3	7.4	8.6	3.7
$CaCO_3$ (%)	57.3	14.0	4.0	78.8	24.4
C (%)	1.9	2.1	0.1	9.6	110.5
Fe (mg/kg)	426.5	115.9	84.2	693.6	27.2
Mn (mg/kg)	226.4	76.5	96.7	378.4	33.8

Table 7. Principal physico-chemical characteristics of the soils of *Tuber magnatum* in valley bottoms of marine and lake sediments of Pliocene and Quaternary (modified by Lulli *et al.* 1991)

Variable	Mean	Std. Dev	Min.	Max.	V.C. (%)
Clay (%)	15.8	7.9	2.1	48.5	50.0
Silt (%)	45.9	14.6	12.4	73.2	31.8
Sand (%)	38.4	20.8	1.7	81.3	54.2
pH_{H_2O}	8.0	0.2	7.6	8.7	2.5
$CaCO_3$ (%)	28.9	7.8	4.9	44.5	27.0
O. M. (%)	2.3	1.3	0.3	13.2	63.3

Table 8. Principal physico-chemical characteristics of the soils of *Tuber magnatum* slopes of marine and lake sediments of Pliocene and Quaternary subjects to landslides (modified by Panini *et al.* 1991)

Variable	Mean	Std. Dev	Min.	Max.	V.C. (%)
Clay (%)	16.0	6.3	1.3	36.6	39.4
Silt (%)	29.2	11.6	1.5	70.7	39.7
Sand (%)	54.9	13.1	18.0	88.5	23.9
pH_{H_2O}	8.1	3.7	6.3	8.6	3.7
$CaCO_3$ (%)	12.3	7.6	0.1	36.8	61.8
O. M. (%)	1.7	1.3	0.3	7.7	71.4

Table 9. Principal physico-chemical characteristics of the soils of *Tuber magnatum* in slopes and valley bottoms of the hills and the mountains where emerge soft marly rocks (modified by Lulli *et al.* 1992)

Variable	Mean	Std. Dev	Min.	Max.	V.C. (%)
Clay (%)	19.8	7.9	4.6	41.4	38.9
Silt (%)	44.9	8.6	24.9	64.5	19.2
Sand (%)	35.3	11.0	16.6	68.0	31.2
pH_{H_2O}	7.9	0.4	6.6	8.4	5.1
$CaCO_3$ (%)	9.8	5.5	2.8	22.1	56.1
O. M. (%)	2.7	2.0	0.5	8.4	73.3

Table 10. Comparison enters the group of membership of each observation and the attribution of the statistical model

Results classification			
Percentage results envisaged by the model for each group*			
Real group	1	2	3
Group 1	91.7	0.0	8.3
Group 2	22.2	55.6	22.2
Group 3	0.0	25.0	75.0
Percentage of observations which were correctly classified by the model: 80.5			

*1 = *Tuber melanosporum;* 2 = *T. aestivum;* 3 = *T. brumale*

Conclusions

Various pedological typologies are recognized as suitable for production of *T. melanosporum, T. aestivum,* and *T. brumale.* The soil, at least down to the depth where ascocarps are found, is always well structured, soft, well aired, and well drained for *T. melanosporum; T. aestivum* develops in a soil environment less aired, less drained, less soft than that of *T. melanosporum.* Physico-chemical laboratory analyses show great variability of values relating to the various chemical parameters and limiting minima of 7.1 and 7.5 respectively for the pH_{H_2O} and pH_{KCl} of soils of *T. melanosporum,* below which development for this species seems to be impossible. *Tuber aestivum* and *T. brumale* can also live in soil environments without carbonates ($CaCO_3$ = 0) in the fine earth, provided that there is a calcareous skeleton in the soil. A Discriminating type statistical analysis, with three levels of classification, shows that best separation between the soils of the three truffle species considered is obtained using only values of the parameters pH_{KCl}, pH_{H_2O}, Organic C, and EDTA extractable Mn. The results of this type of analysis appear to indicate that, with current levels knowledge and relative to *T. melanosporum* and *T. brumale,* these four variables alone are sufficient to obtain a high percentage of correct attribution of soils to one or another species. This is not particularly surprising, given the various morphological characteristics of the sites where these two truffle species occur naturally, especially when they are in proximity to each other. In spite of the fact that no *T. melanosporum* sample was wrongly classified as *T. aestivum,* the margins of uncertainty are still wide because many *T. aestivum* samples are incorrectly classified as pertaining to the two other groups. In this case the observations carried out to date do not appear to be very useful and pedological variables, currently not identified, certainly need to be considered if results of the Discriminating Analysis are to be improved.

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