Chapter 13
Soil Characteristics for *Tuber aestivum* (Syn. *T. uncinatum*)

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13.1 Introduction

Tuber aestivum Vittad. has for several years been considered to be synonymous with *Tuber uncinatum* Chatin (Ceruti et al. 2003; Paolocci et al. 2004; Wedén 2004; Wedén et al. 2004a, b, 2005). A recent multigene phylogenetic study confirmed that *T. aestivum* and *T. uncinatum* are conspecific (Molinier et al. 2013b; see Chap. 3).

Among *Tuber* species of culinary interest, *T. aestivum*, the Burgundy truffle, displays the most extensive geographic range and is found in almost all European countries. Harvests of fruiting bodies have been recorded from Ireland to Azerbaijan and from North Africa to Sweden (see Chap. 3). Gotland Island at a latitude of 57–58 °N is considered to be the northernmost outpost of *T. aestivum* (Wedén and Danell 2001). It is a truffle with great economic value and mostly occurs in natural habitats and habitats that have been previously cultivated and recolonized. Its maturity period occurs in autumn, when soil temperatures remain above 0 °C, protecting fruiting bodies from frost damage.

The aim of this chapter is to define the soil characteristics necessary throughout the life cycle of the Burgundy truffle, including those essential for ascoma

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A. Zambonelli et al. (eds.), *True Truffle (*Tuber *spp.) in the World*, Soil Biology 47,
DOI 10.1007/978-3-319-31436-5_13

formation. The beginning of this chapter describes bedrock characteristics, followed by the physical and chemical properties of soils suitable for the Burgundy truffle.

13.2 Methodology

Data presented in Table 13.1 and Figs. 13.2 to 13.10 have two origins. An initial soil data set was the result of direct contact with truffle growers, technicians, and scientists working on *T. aestivum*, both within and outside Europe. We requested their data from sites known to have produced *T. aestivum* ascoma at least once. A second data set was compiled from papers published in scientific journals and books or included in proceedings of international truffle conferences. We refined our search to consider only those papers which contained soil information clearly indicating that *T. aestivum* ascoma had been collected in these soils. Papers which posed any doubt were rejected.

We will present and discuss here the largest data set ever collected on soils favorable to *T. aestivum* in such a large geographic area; a total of 129 soils from 10 countries were included in this review (Fig. 13.1). This data set cannot be considered to be representative for all situations, yet it can help to form additional hypotheses which should be verified in the future.

Methods of soil analysis were carefully evaluated prior to integrating a data set in the study. We only considered those analyses which used the following standard soil testing methods:

- Soil granulometry with organic matter destruction but without carbonate dissolution prior to analysis with the following size threshold: clay between 0 and 2 μm, silt between 2 and 50 μm, sand between 50 and 2000 μm.
- pH in water (1:5 in volume, ISO 10390).
- Soil organic matter and total nitrogen content determined by dry combustion (ISO 10694 and ISO 13878, respectively).
- Total calcium carbonate content determined by volumetric method (ISO 10693).
- Available phosphorus according to Olsen (ISO 11263) or Joret-Hebert.
- Exchangeable cations (Ca, Mg, and K) and cationic exchange capacity (CEC) were determined either at soil pH (e.g., cobaltihexamine) or at pH 7 (e.g., Metson); both extraction types were considered separately as CEC values are highly dependent on soil pH (Ciesielski and Steckerman 1997).

As units differed from one method to another one, we recalculated several values prior to data processing in order to homogenize the data. We discarded data when soil analysis methods or units were not recorded in the file or the paper. R software (R core team 2013) was used to establish the soil texture triangle and to transform granulometry data with silt to sand thresholds of 63–50 μm (soil texture package: Moeys and Shangguan 2014) and to draw figures (ggplot2 package: Wickham 2009).

Table 13.1 List of the sites investigated and their characteristics, when available: mean annual precipitation (MAP), elevation, nature of the bedrock(s) and of soil (s), most putative host trees, natural site vs. orchard, and source of information

Site	Country	Region	MAP (mm)	Elevation (m AMSL)	Bedrock characteristics	Soil type(s)	Natural truffiere (Yes/No)	Host trees	Information source
Daix	France	Bourgogne	732	330–340	Upper Jurassic, Mid Oxfordian	Anthrosol (calcaric)	No	*Corylus avellana*	H Frochot (pers comm); Molinier et al. (2013a)
Boncourt-sur-Meuse	France	Lorraine	1056	250–300	Upper Jurassic, Oxfordian	Epileptic Cambisols (calcaric, novic), Rendzic Leptosol and Cambisol (hypereutric)/colluvial rendzina, rendzina, and brown calcisol	No	*C. avellana*	Communauté de Communes du Pays de Commercy (pers comm); 12 soil analyses
Rollainville	France	Lorraine	940	360	Jurassic, limestone plateau	Cambisol (calcic)/ brown calcisol	No	*C. avellana*	C Robin (pers comm)
Multi-sites (25)	France	Lorraine, Bourgogne, Franche-Comté, Auvergne	700–1060	700–1060	Cretaceous, upper and mid-Jurassic, Trias—Paleogene (Eocene and Oligocene)	Rendzic Leptosol and Cambisol (calcic)/ rendzina, brown rendzina, and brown calcisol	Yes	*Quercus* sp., *Corylus* sp., *Carpinus* sp., *Pinus* sp., *Tilia* sp., etc.	Le Tacon et al. (1997)
Otterswiller	France	Alsace	–	185–243	–		No	*C. avellana*	H Meyer (pers comm)
Munchhouse 1	France	Alsace	–	220	–	–	No	*C. avellana*, chêne, pin noir	B Vonflie (pers comm)
Munchhouse 2	France	Alsace	–	220	–	–	Yes	*C. avellana*	B Vonflie (pers comm)
Lavoye	France	Lorraine	–	200–270	–	–	No	–	The owner (pers comm)

(continued)

Table 13.1 (continued)

Site	Country	Region	MAP (mm)	Elevation (m AMSL)	Bedrock characteristics	Soil type(s)	Natural truffiere (Yes/No)	Host trees	Information source
Harmonville 1	France	Lorraine	940	313	–	–	No	*Corylus* av., *Quercus* sp., *Pinus nigra*, *Carpinus*, *Betula*, *Tilia*	S Philippe (pers comm)
Harmonville 2	France	Lorraine	940	313	–	–	No	–	S Philippe (pers comm)
Harmonville 3	France	Lorraine	940	313	–	–	No	–	S Philippe (pers comm)
Beine 1 (La Noue d'Aubigny)	France	Champagne-Ardennes	–	140–290	–	–	No	*C. avellana*, *Pinus nigra*, *Carpinus betulus*	JL Dubois (pers comm)
Beine 2 (Les Commelles)	France	Champagne-Ardennes	–	140–290	–	–	No	*C. avellana*, *Pinus nigra*, *Carpinus betulus*	JL Dubois (pers comm)
Humbauville 1	France	Champagne-Ardennes	–	130	–	–	No	*C. avellana*, *Pinus nigra*, oak	M Yverneau (pers comm)
Humbauville 2	France	Champagne-Ardennes	–	130	–	–	No	*C. avellana*, *Pinus nigra*, *Carpinus betulus*	M Yverneau (pers comm)
Blanzac-les-Matha	France	Poitou-Charentes	843	23–76	Jurassic	Calcaric Leptosol (clayic)	Yes	Tilia, *C. avellana*	A Tribot (pers comm)

La Foye-Monjault	France	Poitou-Charentes	814	59	–	Calcaric Leptosol (clayic)	No	*C. avellana*	JJ Sauvaget (pers comm)
Saint-Cybardeaux	France	Poitou-Charentes	750	24–114	–	Cambisol (calcaric, clayic)	Yes	Natural (*Tilia*)/implanted (fence *Corylus*, *Carpinus betulus*)	R Mesnier (pers comm)
Multi-sites (18)	Sweden	Gotland	528	40	Belonging to the Hemse group, stratified, predominantly crystalline, partly fine oolitic limestone, reef-shaped limestone, reef limestone, marly limestone and marlstone, sand limestone, and lime sandstone, and on Högklint limestone, stratified, more or less marly limestone and marlstone and reef limestone		Yes	*Quercus robur*, *C. avellana*	Wedén et al. (2004a, b)
Zapadné Slovensko	Slovakia	Zapadné Slovensko	–	–	–	Rendzic Leptosol, Epileptic Cambisols (calcaric), Luvisol/rendzinas, rendzina Cambisols, Luvisols	Yes	–	Miko et al. (2008); 35 soil analyses
Malé Karpaty	Slovakia	Malé Karpaty	–	–	–	Rendzic Leptosol, Cambisols, Luvisols	Yes	–	Miko et al. (2008)

(continued)

Table 13.1 (continued)

Site	Country	Region	MAP (mm)	Elevation (m AMSL)	Bedrock characteristics	Soil type(s)	Natural truffiere (Yes/No)	Host trees	Information source
Tribeč	Slovakia	Tribec	–	–	–	Rendzic Leptosol, Cambisols, Luvisols	Yes	–	Miko et al. (2008)
Vancouver Island. Nanaimo	Canada	British Columbia	967	32	Upper Cretaceous undivided sedimentary rocks	Canadian System of Soil Classification: orthic dystric brunisol, shallow lithic	No	–	S Berch (pers comm)
Pinczow M	Poland	Nida Basin	600	250	Mesozoic, marlstone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Pinczow SA	Poland	Nida Basin	600	312	Mesozoic, marlstone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Pinczow WR	Poland	Nida Basin	600	295	Mesozoic, marlstone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Pinczow GR	Poland	Nida Basin	600	260	Mesozoic, gypsum	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Przedborz Upland	Poland	–	600	320	Jurassic limestone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)

Chmielnik NW	Poland	Nida Basin	600	228	Marly limestone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Wolynska Upland	Poland	–	550	200	Limestone	–	Yes	–	D Hilszczánska (pers comm); Hilszczánska et al. (2008, 2013)
Spoleto	Italy	Umbria	869	310	Fluvial deposits with coarse fragments from Cretaceous limestones	Eutric Cambisol (Aric)	Yes/No	–	
Six sites	Italy	Provincia di Parma		800–1200	Mesozoic (cretaceous) and Cenozoic (Paleocene, Eocene, Oligocene), marly limestone		Yes	Dominated by *Carpinus*	Gregori (2010)
Two sites	Italy	Provincia di Parma	–	–	–	–	–	–	Gregori (2010)
Provincia de Teramo	Italy	Provincia de Teramo	–	937	Cover detritus-eluvial of the Holocene origin	Mollic Cryosol	Not indicated	*Quercus pubescens*	Menta et al. (2014)
Provincia de Piacenza	Italy	Provincia de Piacenza	–	810	Lutetian limestones and marly limestones alternating marls and calcareous marls	Cambisol (calcaric)	Not indicated	*Q. pubescens*	Menta et al. (2014)
South Liege	Belgium	South Liège	–	240	–	–	Yes	–	The owner (pers comm)

(continued)

Table 13.1 (continued)

Site	Country	Region	MAP (mm)	Elevation (m AMSL)	Bedrock characteristics	Soil type(s)	Natural truffiere (Yes/No)	Host trees	Information source
Guadalajara	Spain	Guadalajara	797	1000	Jurassic and cretaceous limestone and dolomites	Rendzic Leptosol	–	*Quercus faginea*	Menta et al. (2014)
Velkà Chuchle	Czech Republic	Velkà Chuchle	–	–	Silurian limes (Paleozoic)	Rendzic Skeletic Leptosol	Yes	*Corylus*, *Tilia*, *Fraxinus*, etc.	Gryndler et al. (2013)
Kibbutz Bar'am	Israel	Upper Galilee	800	736	Cretaceous (Mesozoic)	Cambisols (dolomitic)	No	–	Y Sitrit (pers comm); Kagan-Zur et al. (2001)
Eger, Heves county	Hungary	Eger, Heves county	600	298	Limestone	Calcic Luvisol	No	–	Z Bratek, A Gogan; Gogan et al. (2012)
Hőgyész, Tolna county	Hungary	Hőgyész, Tolna county	630	210	Tertiary loess	Chernozem and Luvisol	No	–	Z Bratek, A Gogan; Gogan et al. (2012)
Jászság, 20 sampling places	Hungary	Jászság, 20 sampling places	515	<150	Middle Miocene volcanic ash covered with loess	Gleysol (63 %), Chernozem (stagnic) (23 %), Solonchak (4.5 %), Solonetz (9 %)	Yes	–	Z Bratek, A Gogan; Gogan et al. (2012)
South West Germany 1	Germany	South West Germany	890	659	Jurassic	Rendzic Leptosol	Yes	–	Stobbe et al. (2013)
South West Germany 2	Germany	South West Germany	857	772	Jurassic	Rendzic Leptosol	Yes	–	Stobbe et al. (2013)

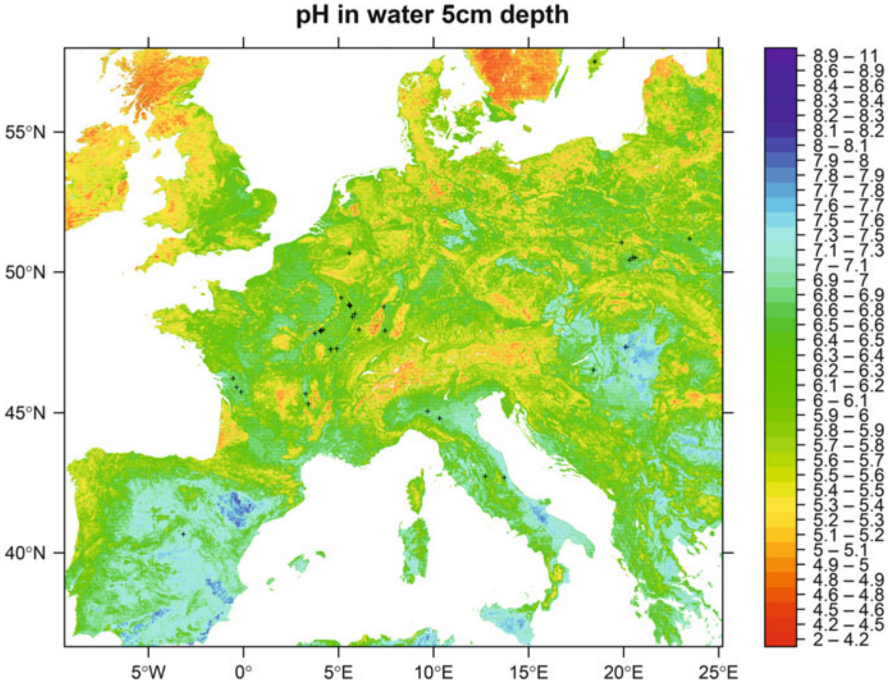

Fig. 13.1 Distribution of soil data set represented over the spatial predictions of soil pH in water at 5 cm depth according to ISRIC—World Soil Information (www.soilgrids.org). Each soil data set used in this study is represented by a cross. SoilGrids1km is a first approximation of soil property predictions at 1 km resolution, using automated global soil mapping. The absolute values of predictions available for download at www.soilgrids.org are presently of limited thematic and spatial accuracy and contain artifacts and missing pixels. Yet the relative values of soil pH in water can be useful to compare distribution of soils favorable to *T. aestivum* between regions

13.3 Nature of the Bedrock and Soil Types

Tuber aestivum fructifies naturally on a range of diverse geological substrates from the Paleozoic era (540 Mya) to present day (Cenozoic), including the Mesozoic (252–66 Mya) (Table 13.1). While bedrock which is sedimentary in origin is the most common trait, *T. aestivum* ascoma can occur on alkaline volcanic substrates and on quaternary formations (loess and glacial formations). Below are examples of fructification situations in countries for which information has been found.

France In northeastern France, the parent rock dates from the Jurassic, the Cretaceous, and, to a lesser extent, to the Trias periods. In central France, around Paris and Limagne (near Clermont-Ferrand), *T. aestivum* is found on limestone from the Tertiary (Eocene and Oligocene) period. In some cases, the parent material is a gravel formation dating from the glaciation period (Table 13.1; Le Tacon et al. 1997). In most documented cases, *T. aestivum* has been found on Rendzic Leptosol and Calcic to Calcaric Cambisol.

Czech Republic (Gryndler et al. 2013) A productive area near Prague is Rendzic Leptosol (Skeletic) formed on Silurian limestone.

Germany (South West, Baden-Württemberg, Stobbe et al. 2012, 2013) A broad range of calcareous bedrocks have been associated with truffle sites (*T. aestivum* was recorded on 116 of 121 sites where truffles have been found). The Jurassic rock formations of the Swabian Jura and the Rhine valley slopes, as well as Quaternary glacial deposits of the northern pre-Alps, are the most common bedrocks, followed by molasses, loess, and volcanic tuff.

Hungary (Bratek and Halász 2005; Gogan et al. 2012) *T. aestivum* is uniformly spread in the Carpathian basin. The bedrock has various origins: limestone, tertiary loess, middle Miocene volcanic ashes covered with loess, etc. The most famous *T. aestivum* habitat is located in the Jászság region. This area is situated in the middle of Hungary, between the Danube and Tisza rivers. This flatland area is basically covered by river alluviums leading to Chernozems, Fluvisols, Solonchaks, and Arenosols formation.

Italy The most represented situations in Tuscany are the marly limestones (“Alberese” and “Macigno di Londa” formations), the stratified limestones (Cretaceous and Jurassic), and the coarse sediments (sands mixed pebbles in sandy matrix) (Gardin 2005). Around Parma, burgundy truffle grows on land derived from sedimentary rock (limestone marl) Mesozoic (Cretaceous) and Cenozoic (Paleocene, Eocene, Oligocene), called Flysch (Belloli et al. 1999; Gregori 2010).

Poland Parent soil material suitable for *T. aestivum* in Poland is from Cretaceous marlstone, marly limestone, and gypsum (Hilszczánska et al. 2008) and from Miocene clays and sand. Soil cover consists primarily of Cambisols and Chernozems (Hilszczánska et al. 2013).

Slovakia (Miko et al. 2008) Ascoma are harvested in clayey soils rich in organic matter. Soils are Rendzic Leptosols, Cambisols, or Luvisols.

Spain (García-Montero et al. 2014; Menta et al. 2014) *T. aestivum* is mainly present in central Spain (province of Guadalajara) on Jurassic and Cretaceous limestones and dolomites. Soils are Lithic and Rendzic Leptosols.

Sweden (Wedén et al. 2004a) The bedrock belongs to five different groups (from the youngest to the oldest): (1) bedrock belonging to the Hemse group, partly fine oolitic limestone, reef-shaped limestone, reef limestone, marly limestone, and marlstone (nine sites); (2) Mulde marlstone, marlstone and marly limestone (one site); (3) Halla limestone, stratified, more or less marly limestone and reef limestone (one site); (4) Slite group, stratified, crystalline limestone and reef limestone, marlstone and marly limestone, sand limestone, and lime sandstone (six sites); and (5) Högklint limestone, stratified, more or less marly limestone and marlstone and reef limestone (one site) (Wedén et al. 2004a).

United Kingdom (Hall et al. 2007) Though rarely found, *T. aestivum* is mainly present in southern England, Scotland, and Wales, in shallow, lime-rich soils over Secondary and Tertiary limestones.

Israel *T. aestivum* does not appear to occur naturally in this country. Ascoma have been found in planted areas in Upper Galilee on bedrock from Cretaceous with dolomitic soils (Turgeman et al. 2012).

Canada (Berch pers comm) *T. aestivum* does not occur naturally in Canada and has only been found in one orchard planted following liming treatment on Vancouver Island on Mesozoic-upper Cretaceous undivided sedimentary rocks. According to Canadian System of Soil Classification, the soils are orthic dystric brunisol, shallow lithic, glaciomarine deposits (Berch and Bonito 2014).

13.4 Physical Properties

13.4.1 Soil Texture

Tuber aestivum can be found in soils with a large variety of textures as shown in the soil textural triangle (Fig. 13.2) established from 86 soil analyses of productive sites: clay, silty clay, silty clay loam, clay loam, loam, sandy loam, sandy clay loam, silt loam. The broad range in soil particle size distribution demonstrates that *T. aestivum* has a wider soil texture tolerance than the Périgord black truffle (see Chap. 11). Clearly, fruiting bodies can be harvested in soils that contain low to high sand percentages (2.8–79.8 %), low to high silt percentages (9.8–67.4 %), and low to medium clay percentages (5–55 %). Only soils with extreme textures have been excluded (sand, silt, and clay contents superior to 80 %, 70 %, and 60 %, respectively) (Fig. 13.2).

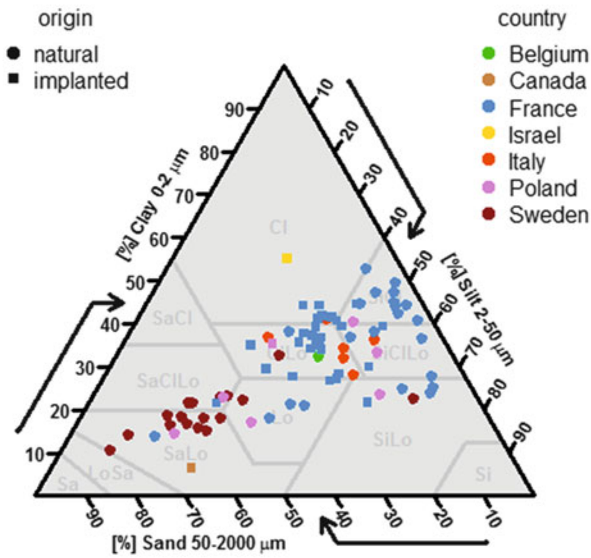

Fig. 13.2 Soil texture (USDA texture *triangle*) of the sites in which *T. aestivum* ascoma have been harvested (83 soils of 7 countries). Natural forest sites are represented by a *square* and implanted sites by a round point. Each site is represented by a colored point specific for each country

13.4.2 Soil Water-Holding Capacity and Drainage

Many soils of *T. aestivum* truffle orchards are characterized by a high water-holding capacity due to their silty clayey texture and/or their high organic matter content. High soil water availability is favorable to fruiting body production by lowering water stresses during drought periods. The topographic position at the base of slopes is particularly favorable, as observed in temperate climates. Under Mediterranean climate, ascoma production in summer months is often canceled due to insufficient water availability.

The bedrock is often cracked, and the presence of stones, associated with the granular and stable structure, ensures good drainage. Proper water infiltration prevents erosion (on sloped terrain) or waterlogging (on flat terrain), the latter being deleterious for mycorrhiza physiology. In Italy, the production sites are generally located on shallow soils, with depths of roughly 50–60 cm and consistently well drained (Gardin 2005).

13.4.3 Soil Structure

In sites where *T. aestivum* is harvested, the soil structure is generally good to excellent, being highly loose and stable (with a granular structure). Organic matter content together with the presence of $CaCO_3$ provides the soils with good structure, which can compensate for the clayey texture often found in eastern France. A loose and stable structure ensures high porosity throughout the year, which in turn increases soil water infiltration and aeration. Yet, soil structure and porosity also depend on cultivation practices. Soil compaction due to heavy traffic and/or intensive grazing in wet soils should be avoided.

13.5 Chemical Properties

13.5.1 pH

The meta-analysis indicates a relatively large range of soil pH variation (from slightly acidic, neutral to basic). Thus, the range of soil pH in water where *T. aestivum* fructifies (5.9–8.4) is quite similar to the pH of soils where *Tuber melanosporum* Vittad. is harvested (5.5–8.4) (Jaillard et al. 2014; see Chap. 11).

Soil pH is more often basic, due to the presence of limestone in all soil horizons. On limestone-derived soils, one of the factors explaining variations in pH levels is the content and composition of the soil organic matter. For example, a negative correlation between soil organic matter content and water pH (Spearman's rho = −0.72) can be observed in the implanted truffle grounds of France (solely limestone-derived soils) (Fig. 13.3).

The distribution of soil pH in water is similar for both natural sites and orchards (Fig. 13.4).

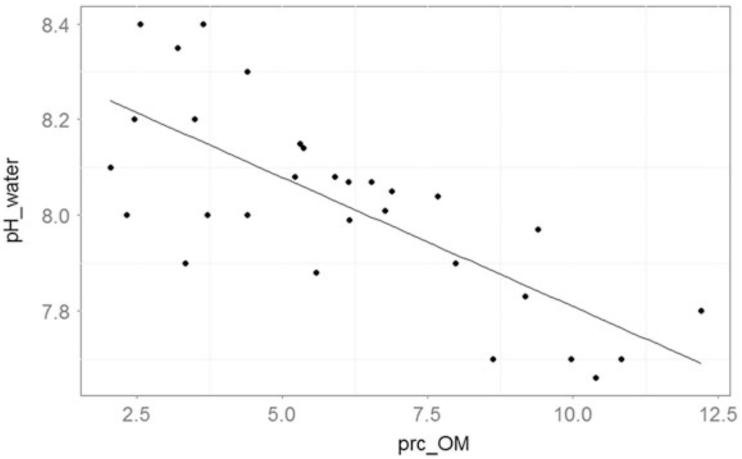

Fig. 13.3 Relationship between soil pH in water (pH_water) and organic matter content (in %, organic matter: prc_OM) for the French truffle orchard considered in this study (among 129 soils from 10 countries, we considered only limestone-derived soils that had been subject to the same historical uses prior to implanting *T. aestivum* and which provided a sufficient number of samples to assess the relationship between soil pH in water and organic matter content)

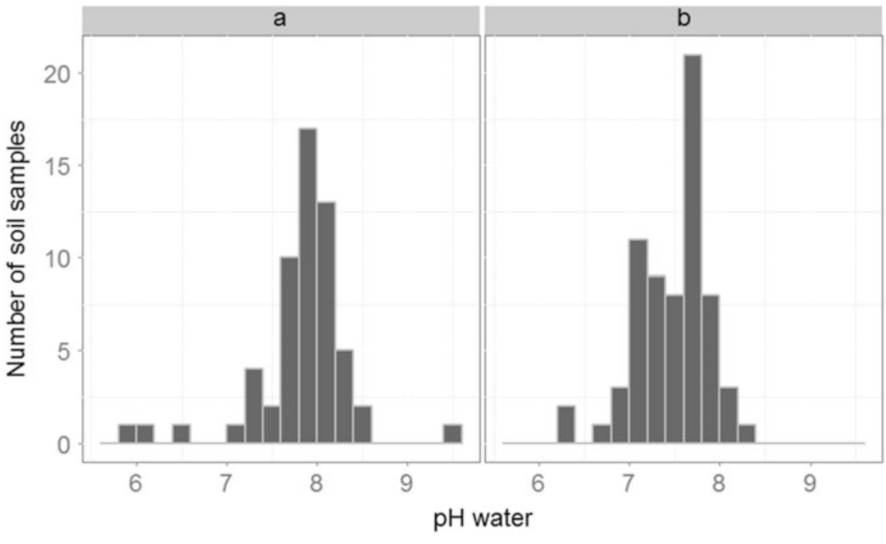

Fig. 13.4 Distribution of soil pH (in water) in sites where *T. aestivum* ascoma were harvested: orchards (**a**) and natural forest sites (**b**)

13.5.2 Carbonates

Soil carbonate content is highly variable, with values ranging between 0 and 69 %. Our data set shows differences of soil carbonate distribution between natural and implanted truffle orchards (Fig. 13.5). No direct correlation between Figs. 13.4 and 13.5 can be made as several soils were analyzed only for pH in water and not for carbonate content. *Tuber aestivum* orchards are implanted in soils that tend to be more carbonated than soils in which *T. aestivum* occurs naturally. The soil calcium carbonate content ranges from 0 to 55 % in natural forest soils where *T. aestivum* is harvested, but it is mainly harvested in soils with limited amounts of calcium carbonate (0.1–1.5 %) and most of the natural sites with a $CaCO_3$ content lower than 20 %. These results reinforce findings that unlike truffles with higher commercial value such as *Tuber magnatum* Pico and *T. melanosporum*, *T. aestivum* is able to live and form fruiting bodies in soils poor in carbonates. In productive orchards, the soil calcium carbonate content ranges from 3 to 80 %.

Although that most of the times *T. aestivum* orchards are implanted on carbonated soils, the contents of total or active calcium carbonate are not relevant descriptors as assumed by several authors (Callot 1999; García-Montero et al. 2007; Jaillard et al. 2008). Indeed, in natural habitats *T. aestivum* ascoma can be found up to pH 5.9 in the upper part of the soils (according to this data set which may be not representative of all situations).

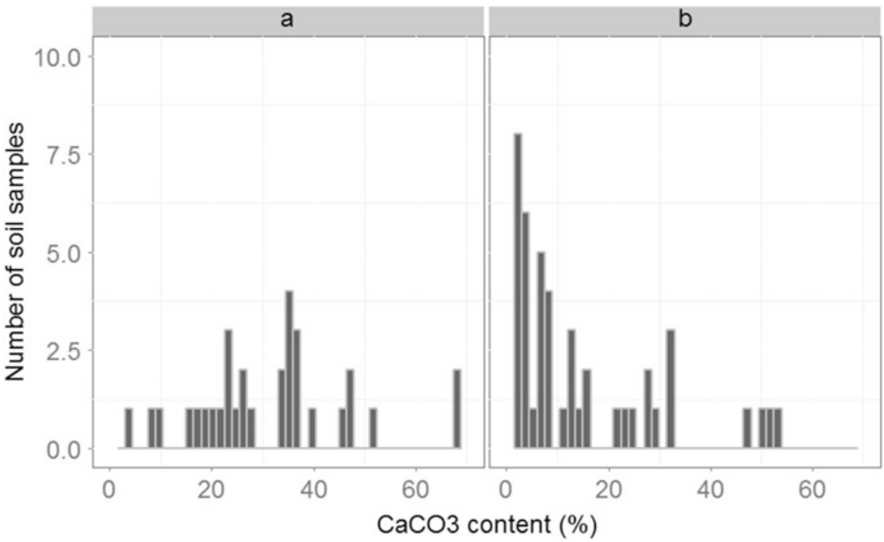

Fig. 13.5 Distribution of soil carbonates content in soils of orchards (**a**) and in soils of natural or secondary forest sites (**b**)

13.5.3 Organic Matter

The range of organic matter is considerable (0.7–21.2 %). In noncultivated carbonated soils, $CaCO_3$ coats the organic matter and prevents mineralization despite the high levels of biological activity. The organic matter combined with $CaCO_3$ is partly responsible for the exemplary structure of Burgundy truffle soils found in eastern France (Le Tacon et al. 1997). The data collected show that most of the truffle orchards display relatively low organic matter content, which is most likely related to the land's agricultural history (i.e., it is difficult to implant truffles in soils of a former forest), whereas natural truffle grounds display the highest organic matter content (Fig. 13.6).

The cationic exchange capacity (CEC) ranges from 5 to 30 cmol+ kg^{-1} in orchards and from 15 to 45 cmol+ kg^{-1} in natural or secondary forest sites where the content of organic matter is often higher than in truffle orchards. CEC of calcic and calcaric soils [Rendzic Leptosols, Epileptic Cambisols (calcaric), Cambisols (calcaric), Cambisols (hypereutric)] is higher than CEC of acidic soils although values vary considerably (Badeau et al. 1999). At neutral or basic pH levels, the CEC increases in proportion to the organic matter content (Badeau et al. 1999). The data collected show that, despite higher pH in soils with implanted truffles (mostly former agricultural soils), the proportion of high CEC soils is relatively low due to their lower organic matter content (Fig. 13.7).

Most of the time, the C/N ratio of the *T. aestivum* soils is quite low, at around 10–12, which is characteristic of fertile soils rich in stabilized organic matter. Only a few soils showed a C/N ratio higher than 20 (Fig. 13.8). A low C/N ratio confers to

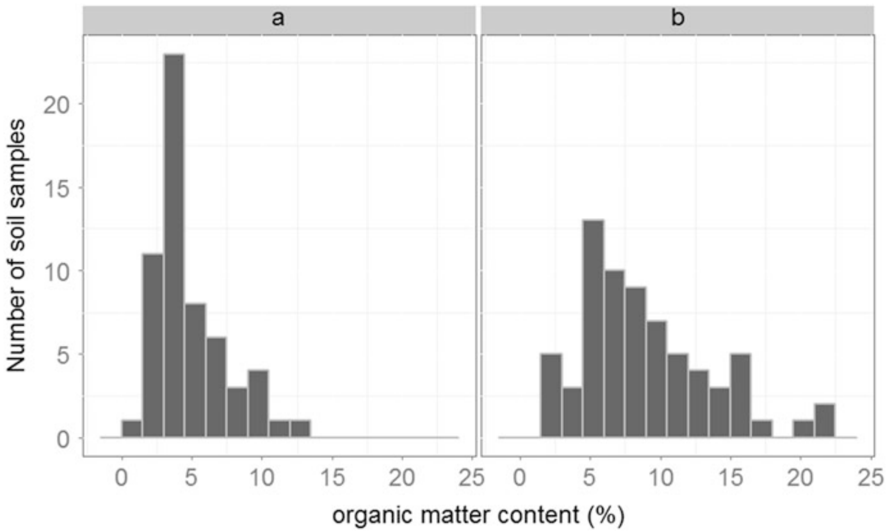

Fig. 13.6 Distribution of soils according to their organic matter content. Orchards (**a**) and natural forest sites (**b**)

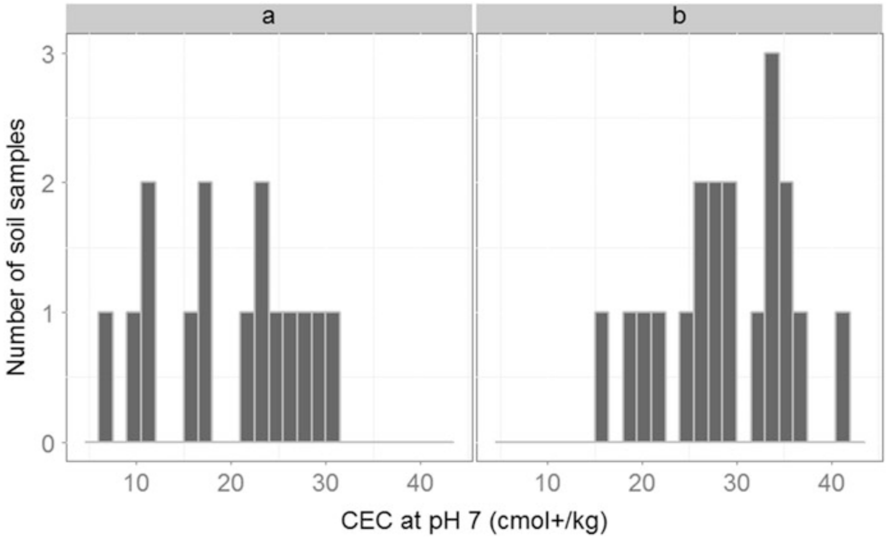

Fig. 13.7 Distribution of soils according to their CEC at pH 7. Orchards (**a**) and natural or secondary forest sites (**b**)

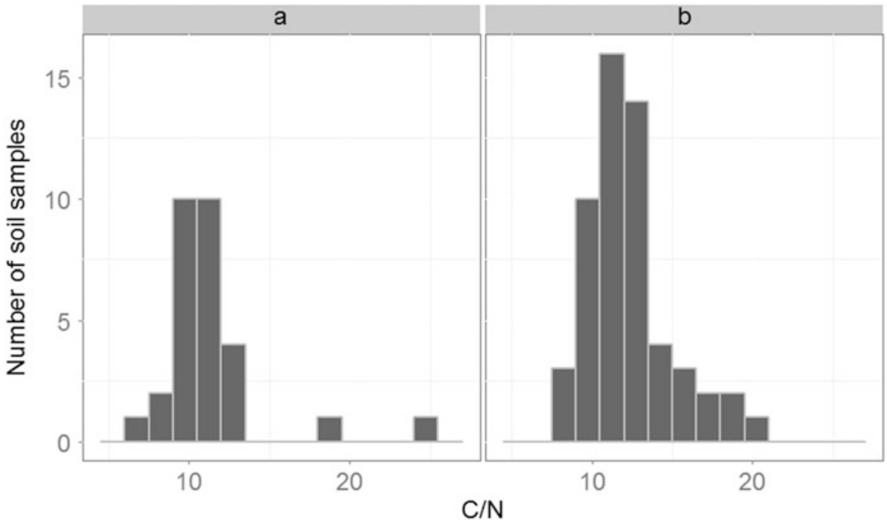

Fig. 13.8 Distribution of soils according to their C/N ratio. Orchards (**a**) and natural sites (**b**). *Tuber aestivum* ascoma have been harvested on each of the sites included in the graph

the microorganisms in soils the capacity to decompose the organic matter and, thus, to supply mineral nitrogen to the ecosystem. It is interesting to note that 90 % of agricultural soils have a C/N ratio less than 11 when compared to 8 % of forest soils. Nearly 50 % of agricultural soils have a C/N ratio ranging between 9 and

10 (Badeau et al. 1999). Thus, for this parameter, the collected data once again underlines that the main differences in soil properties between implanted and natural *T. aestivum* production sites relate directly to their original use (agricultural or forest land).

13.5.4 Nutrients

The available phosphorus content in soils (Joret-Hebert or Olsen methods) is comprised between 0.0035 and 0.51 g P kg^{-1}. Most of the soils show low concentrations of available P (between 0.0035 and 0.1 g P kg^{-1}) (Fig. 13.9) which is characteristic of the majority of limestone soils. Le Tacon et al. (1997) analyzed 25 sites in France which indicated a general range of available P values from 0.009 to 0.044 g P kg^{-1}.

Soils suitable for *T. aestivum* are saturated in exchangeable Ca (66–97 %), and the ratio of exchangeable K and Mg over the CEC is relatively low (1.3–15 % and 1.4–19 %, respectively). A K:Mg ratio over 2 has a negative effect on plants' uptake of Mg (Ericksson et al. 1997 cited in Hilszczánska et al. 2013) ; Mg availability problems may occur more often or may be more pronounced when soil available K content is twice as high as the Mg content. The exchangeable K to Mg ratio is never >2 in implanted *T. aestivum* orchards, whereas it is higher than 2 in a few naturally productive areas (Fig. 13.10). It should be noted that Mg deficiencies due to excess K content have to date not been documented for truffle production, and it

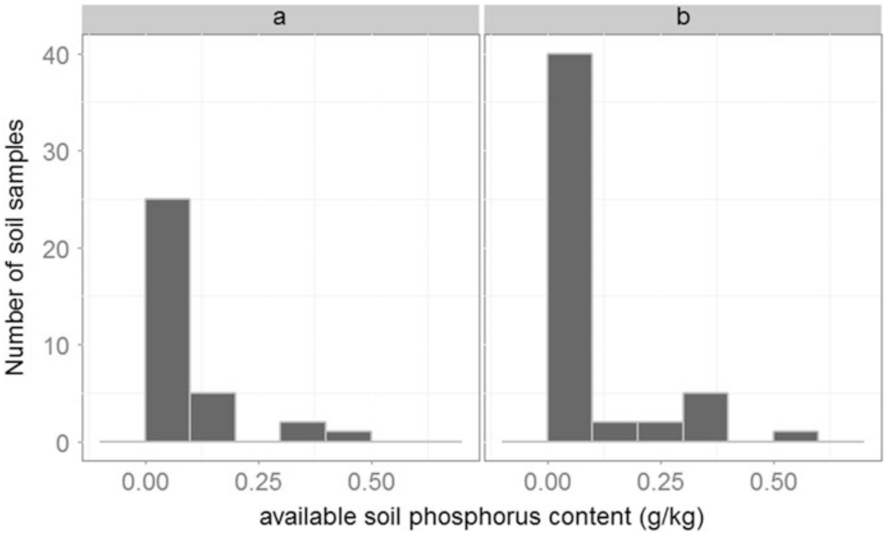

Fig. 13.9 Distribution of soils according to their phosphorus content. Orchards (**a**) and natural or secondary forest sites (**b**)

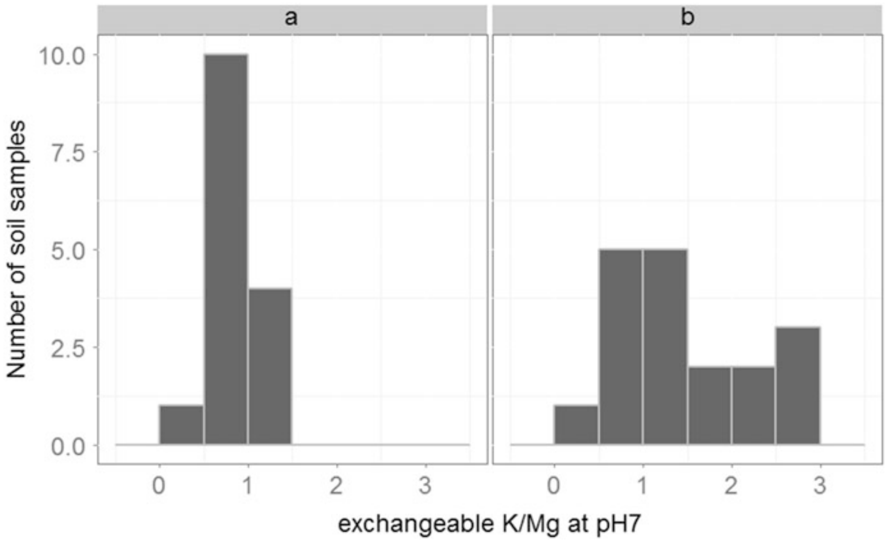

Fig. 13.10 Distribution of soils according to their K:Mg ratio measured at pH 7. Orchards (**a**) and natural sites (**b**). *Tuber aestivum* ascoma have been harvested on each of the sites included in the graph

remains difficult to draw conclusions for cases of higher than 2 K:Mg ratios in natural truffle orchards.

13.6 Conclusions

In natural or seminatural conditions, T. *aestivum* ascoma are found in soils exhibiting a wide range of pH levels, from slightly acidic to neutral and basic, when limestone is present. In plantations, the soil pH is more often basic. Many soils in which *T. aestivum* are found are characterized by a high water-holding capacity due to their silty clayey texture and/or their high organic matter content. Moreover, these sites are often well supplied with water due to their topographic positioning at the base of slopes. This high soil water availability is favorable to fruiting body production by decreasing water stress during drought periods. *Tuber aestivum* can be cultivated in almost all neutral to alkaline soils showing small to medium compactness (Bragato et al. 2009). The ecological and pedo-climatic requirements of the Burgundy truffle confer to this species an increased capacity to adapt to many environments. Anthropogenic areas such as road and rail embankments are emblematic and also favorable to the development of this truffle (Gardin 2005). The large diversity of host trees should also be emphasized (Table 13.1). This high flexibility explains why *T. aestivum* can be found spread across Europe. In many cases, in natural habitats or planted areas, *T. aestivum* is found together with other truffles species, including *T. melanosporum*.

The main challenges for future research related to *T. aestivum* soils will be to precisely identify optimal soil conditions for the initiation and growth of ascoma and to characterize conditions which facilitate the colonization and persistence of *T. aestivum* mycorrhizas in root systems. This knowledge should help to establish future best management practices for ascoma production and to optimize the current ones (irrigation, soil tillage, mulching, supplies of organic matter, micronutrients, etc.).

In order to extend the study to more sites, we invite the readers to send additional soil data sets of sites known to produce *T. aestivum*; please contact the corresponding author for guidelines.

Acknowledgments We would like to thank all colleagues and truffle growers listed below, including those who wish to remain anonymous and who provided soil data and/or published literature at local/regional/national levels: France, Jean-Sébastien Pousse (Codecom Pays de Commercy), Henri Frochot (Daix), Marc Yverneau (Humbauville), Bernard Vonflie (Munchhouse), Hubert Meyer (Otterswiller), Jean-Luc Dubois (Beine), Jean-Jacques Sauvaget (La Foye Montjault), Régis Mesnier (Saint-Cybardeaux), and Alain Tribot (Blanzac-les-Matha); Italy, Gilberto Bragato (CRA Gorizia) and Gianluigi Gregori (Sant'Angelo in Vado); Hungary, Andrea Gógán Csorbai (Szent István University, Gödöllő) and Zoltán Bratek (Eötvös Loránd University, Budapest); Poland, Dorota Hilszczanska (Forest Research Institute, Raszyn); Slovakia, Juraj Chlpik (Slovak University of Agriculture, Nitra); Spain, Daniel Oliach (Centre Tecnologic Forestal de Catalunya, Solsona); Israël, Yaron Sitrit (Ben-Gurion University of the Negev, Beer-Sheva); and Canada, Shannon Berch (British Columbia Ministry of Environment, Victoria).

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