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Julie Dabkowski, Léa Beaumont. Rise and decline of Holocene tufas across Europe: exploring east/west and north/south similarities and differences in their development. *Journal of Quaternary Science*, In press, 10.1002/jqs.3637 . hal-04621984

HAL Id: hal-04621984

<https://hal.science/hal-04621984>

Submitted on 24 Jun 2024

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Rise and decline of Holocene tufas across Europe: exploring east/west and north/south similarities and differences in their development

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Received 21 August 2023; Revised 21 May 2024; Accepted 27 May 2024

ABSTRACT: An extended inventory of 82 well-dated European calcareous tufas is used to discuss the timing and amplitude of their onset, maximum and decline; in particular differences from east to west and between the Mediterranean area and the rest of Europe. Eastern deposits start to develop and reach their maximum slightly earlier than western tufas. Strong east–west differences in the timing and intensity of the climatic improvement during the first half of the Holocene explain the earlier development of eastern tufas compared with the west. The strongest differences are observed between Mediterranean deposits and other European tufas both in their development and decline, whether all or only fluvial deposits are considered, reflecting the important decoupling between Mediterranean and mid-latitude climate records. During the Late Holocene, the earlier and more pronounced tufa decline observed in European mid-latitudes is likely to result from more intense and rapid deforestation compared with the Mediterranean region.

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KEYWORDS: anthropisation; calcareous tufas; climate impact; Europe; Holocene; ‘Late Holocene tufa decline’

Introduction

Calcareous tufas are one of the few continental archives that can provide a true synergistic and independent record of both palaeoenvironmental (including physical, faunal and floral changes) and palaeoclimatic information (especially from calcite stable isotopes), while they can also be precisely and objectively dated (Andrews, 2006; Pedley, 2009; Capezzuoli et al., 2014; Dabkowski, 2014). This has led to a growing research interest in these open-air carbonate deposits in recent decades, reflected in a rapidly increasing number of publications, especially on Holocene tufas as they are more abundant and better preserved than older deposits. A recent review of this literature has fostered a detailed discussion of the widely debated postulate of a ‘Late Holocene tufa decline’ in Europe (Goudie et al., 1993) and has demonstrated that this is actually a general view of a rather complex trend: while fluvial tufas show a systematic decline from ca. 5 ka cal. BP, there is no general trend in the evolution of proximal (spring-fed) or lacustrine tufas (Dabkowski, 2020). This feature is likely to reflect the increasing impact of human activities on landscapes as several authors have noted a chronological concordance between the onset of the tufa decline and the beginning of the Bronze Age, when deforestation, pastoralism and river management rapidly increased (Alexandrowicz and Skoczylas, 2017; González-Amuchastegui and Serrano, 2015a; Lippmann and Vernet, 1986; Taylor et al., 1998; Vaudour, 1994, 1986); these activities might affect fluvial systems more systematically than other types of deposit (Antoine et al., 2002; Dabkowski, 2020; Pastre et al., 2001).

The sensitivity of calcareous tufas to climatic changes has also long been demonstrated as they develop preferentially during interglacials (Pentecost, 1995, 1993) and can be used as markers of temperate and/or humid periods, especially in

semi-arid areas (Butzer et al., 1978; Dabkowski et al., 2022; Delgado Castilla, 2009; Hamdan and Brook, 2015; Nicod, 2000; von der Meden et al., 2022). The previous review also showed (but did not discuss in detail) that tufa deposits in Europe do not start developing synchronously with the increase in temperatures and precipitation at the beginning of the Holocene: a few sites are even assigned to the Lateglacial, before their number rapidly increased during the Early Holocene (Dabkowski, 2020). Furthermore, although the widespread distribution of calcareous tufas at temperate latitudes, especially in areas with carbonate bedrock, has long been established (Ford and Pedley, 1996; Pentecost, 2005, 1995), possible changes in this distribution through time have received little or no attention. However, the effects of Holocene climatic changes on local/regional environments and climates have shown different dynamics and intensities across Europe (Horsák et al., 2020; Mauri et al., 2015; McDermott et al., 2011), which may lead to regional differences in the timing of tufa development.

In this paper, we propose to cross-reference both chronological and spatial data on the Holocene distribution of calcareous tufas. Using the updated inventory of well-dated deposits (Dabkowski, 2020), differences across Europe in the timing and intensity of the tufa onset and decline during the Holocene will be investigated.

Tufa distribution in Europe during the Holocene: an updated inventory

Data summarised here were collected from 97 references (journal articles, previous reviews, books, technical reports, etc; Table 1). Only publications with strong chronological information (from radiometric dating or biostratigraphy) were included. Compared with Dabkowski (2020), 17 scientific papers were added, eight of which were published after the

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Table 1. List of sites and related bibliography included in this review. Sites are first classified by country (in alphabetical order of their ISO3161-1 alpha-2 code) then by alphabetical order of the site main name. Sites marked by an asterisk are new compared with the previous review by Dabkowski (2020).

AT: AUSTRIA	
St Magdalena	Fritz, 1976
BE: BELGIUM	
Annevoie-Rouillon	Geurts, 1976/Quinif, 2012/Paepe, 1965
Buzenol	Couteaux, 1969
Ethe (La Source du Cron)	Vaudour, 1986/Couteaux, 1969
Orval Abbaye	Couteaux, 1969
Treignes	Mullenders et al., 1963/Geurts, 1976/Vaudour, 1986/Janssen and Swennen, 1997
Vierset-Barse (Houyoux valley)	Geurts, 1976/Franco et al., 2008
Villiers-Devant-Orval (Le Chameleux)	Vaudour, 1986/Paepe et al., 1970/Souchez and Paepe, 1972/Geurts, 1976/Pazdur and Pazdur, 1990/Janssen and Swennen, 1999
BY: BELARUS	
Ptich	Makhnach et al., 2004
CZ: CZECHIA	
Svaty Jan pod Skalou	Žák et al., 2002
DE: GERMANY	
Bad Laer	Hiltermann, 1977
Ammer river*	Heidgen et al., 2020
EE: ESTONIA	
Lake Äntu Sinijärv	Laumets et al., 2014
Varangu	Kalm & Sohar, 2010/Sohar & Meidla, 2010
ES: SPAIN	
Alcaraz	Andrews et al., 2000/Taylor et al., 1998
Añamaza*	Luzón et al., 2011; Sancho et al., 2015
Ebrón*	Sancho et al., 2015
Galera*	Wolf et al., 2021; Wackenheim et al., 2023
Laguna Redondilla	Andrews et al., 2000
Mesa*	Sancho et al., 2015
Molinar valley	González-Amuchastegui and Serano, 2015a, 2015b
Piedra*	Sancho et al., 2015
Purón valley	González-Amuchastegui and Serano, 2015a, 2015b
Queiles valley (Moncayo Natural Park)	Aranbarri et al., 2016
Sedanillo valley	González-Amuchastegui and Serano, 2015a, 2015b
Tubilla del aqua	González-Amuchastegui and Serano, 2015a, 2015b
Val valley	Aranbarri et al., 2016
FR: FRANCE	
Calais coastal plain (several sites including Guînes)	Sommé, 2006/Van der Woude and Roeleveld, 1985
Clénay (vallée de la Norges)	Clair et al., 1972
Daours	Limondin-Lozouet et al., 2013
Jouques	Vaudour, 1994/Ollivier et al., 2006/Nicod, 2010/Nicol-Pichard, 1986
La Vis	Ambert, 1986/Vaudour, 1986
Meyrargues (Grand Vallat)	Vaudour, 1994/Ollivier et al., 2006/Nicod, 2010/Magnin et al., 1990
Pont-de-Joux	Vaudour, 1994/Ollivier et al., 2006/Nicod, 2010/Bonifay, 1986
Saint Gilhem le Désert	Ambert, 1986
Saint-Antonin	Vaudour, 1994/Ollivier et al., 2006/Nicod, 2010/Guendon and Vaudour, 1981/Guendon et al., 2003/Ali et al., 2003
Saint-Germain-le-Vasson	Limondin and Preece, 2004/Limondin-Lozouet et al., 2005
Scarpe valley (Hamblain-les-Prés)	Sommé, 2006/Emontspohl, 1994
St Momelin	Sommé, 2006/Van der Woude and Roeleveld, 1985
Vauvenargues	Vaudour, 1994/Ollivier et al., 2006/Nicod, 2010/Del Giovine, 1986/Magnin and Thinon, 1988
GB: GREAT BRITAIN	
Alport (Lathkill valley)	Andrews et al., 1994
Caerwys	Garnett et al., 2006
Inchrory (Scotland)	Preece et al., 1984/Faulkner and Brazier, 2016
Wateringsbury	Garnett et al., 2004
HR: CROATIA	
Krka	Horvatinčić et al., 2000
Plitvice	Roglic, 1977/Srdoč, 1985/Srdoč et al., 1980, 1994/Horvatinčić et al., 2000
Zrmanja*	Barešić et al., 2021
IT: ITALY	
Le Marmore*	Calderini et al., 1998
Paestum	Lippman and Vernet, /Amato et al., 2009
Pecora river*	Pieruccini et al., 2021
Triponzo	Fubelli et al., 2013/Vinken, 1968
Velino river*	Soligo et al., 2002
LU: LUXEMBOURG	
Direndall	Meyrick, 2000/Dabkowski et al., 2015/Granai et al., 2020
Loschbour	Gob et al., 1984/Brou et al., 2014

(Continued)

Table 1. (Continued)

LV: LATVIA	
Raganu*	Gałka et al., 2021
PL: POLAND	
Bobolice*	Dobrowolski et al., 2019
Dolina Eliaszkówki Nature Reserve	Alexandrowicz and Skoczylas, 2017
Homole Gorge	Alexandrowicz, 1996/Alexandrowicz et al., 2016
Komarów	Dobrowolski et al., 2016
Krzywice	Dobrowolski et al., 2002/Alexandrowicz et al., 1994/Pazdur et al., 2002
Laski	Gradziński et al., 2001
Ociemny stream	Alexandrowicz et al., 2016/Alexandrowicz and Skoczylas, 2017
Orgatowo*	Dobrowolski et al., 2019
Płaśnie	Alexandrowicz, 2013/Alexandrowicz et al., 2016
Puszcza Romincka*	Apolinarska et al., 2023
Raławka	Pazdur et al., 1988/Szulc, 1983
Rudka	Dobrowolski et al., 2002/Pazdur et al., 2002
Rzeczusnia	Pazdur et al., 1988
Sąspowska valley	Alexandrowicz, 1983/Gradziński et al., 2017
Sieradowice	Pazdur et al., 1988
Skotnicki stream	Alexandrowicz et al., 2016
Sokolica*	Dobrowolski et al., 2019
Trzebieńce	Pazdur et al., 1988
Turtul*	Apolinarska et al., 2022
Tylka	Alexandrowicz, 2013/Alexandrowicz et al., 2016
Zawadówka	Dobrowolski et al., 2005
RO: ROMANIA	
Valea Morii*	Gałka et al., 2018
SE: SWEDEN	
Pipers Mosse*	Gedda et al., 1999; Gedda, 2001
Valleröds Mosse*	Gedda, 2001; 2006
SK: SLOVAKIA	
Háj	Gradziński et al., 2013
Hrhov	Gradziński et al., 2013
Mituchovci	Hájek et al., 2016/Dabkowski et al., 2019

2020 review, i.e. in the last three years (Apolinarska et al., 2022, 2023; Barešić et al., 2021; Gałka et al., 2021; Heidgen et al., 2020; Pieruccini et al., 2021; Wackenheimer et al., 2023; Wolf et al., 2021), while the nine others were mostly published in the last decade (Calderini et al., 1998; Dobrowolski et al., 2019; Gałka et al., 2018; Gedda, 2001, 2006; Gedda et al., 1999; Luzón et al., 2011; Sancho et al., 2015; Soligo et al., 2002), confirming the strong and growing research interest in tufa deposits.

Nineteen sites from eight different countries across Europe (Croatia, Germany, Italy, Lithuania, Poland, Romania, Spain and Sweden) have been added to the original inventory. A total of 82 inventoried sites are discussed here, representing 16 countries and covering almost the whole of Europe from Scotland to Spain and Italy and from the Atlantic coast to Belarus and Estonia (Table 1 and Fig. 1). Only the high latitudes (i.e. Scandinavia) are not represented in the inventory (except for a few sites from southern Sweden). Two factors may explain the apparent absence of tufa deposits in this area: (1) it corresponds to the Fennoscandian Shield, which consists mainly of metamorphic gneisses and greenstones and only few carbonates; and (2) the subarctic climate may be both too cold and too dry to allow tufa precipitation (Pentecost, 1995).

Among the 19 newly inventoried sites, 10 are fluvial deposits and the other nine are proximal tufas (spring-fed fen), giving a total of 41 intermediate (fluvial) tufas (half of the entire dataset) and 26 proximal deposits, including spring-fed fen and perched spring-line tufas, as defined by Capezzuoli et al. (2014). The remaining 15 locations are lacustrine tufas (Fig. 1).

Figure 2 shows the temporal distribution of the 82 sites inventoried since the Lateglacial. This extended inventory reinforces the previous conclusion: after a maximum reached

during the Atlantic, not all tufa deposits are significantly affected by the Late Holocene tufa decline and only those formed in fluvial environments (i.e. intermediate) are affected by a strong decrease from ca. 6–5 ka cal. BP (Dabkowski, 2020). This dataset also documents the onset of European tufas at the beginning of the Holocene and even since the Lateglacial at some fluvial and lacustrine sites (Fig. 2). As the inventoried deposits are widely distributed across Europe (Fig. 1), the time distribution of Holocene tufas will now be considered spatially, comparing western with eastern and northern with southern data.

East/west comparisons

The 10th meridian was chosen to separate western from eastern tufas, as it roughly corresponds to the present-day transition between the European oceanic and continental climates and allows the dataset to be divided into two equal groups of 41 sites (Fig. 1 and Tab. 2). In the west, two thirds of the sites are fluvial deposits ($n=27$), whereas they represent only one third of the eastern tufas ($n=14$; Table 2). This disequilibrium reflects the predominance of fluvial deposits in the most complete regional surveys from southern France and northern Spain (González Martín and González-Amuchastegui, 2014; González-Amuchastegui and Serrano, 2015b, 2015a; Ollivier et al., 2006; Vaudour, 1994) and leads to an overrepresentation of fluvial tufas in the west compared with the east: two thirds of all inventoried intermediate tufas are located in the west.

The distribution of eastern and western tufas through time is shown in Fig. 3. Eastern deposits start to develop during the Lateglacial and reach a maximum between 9 and 5.5 ka cal. BP, slightly earlier than the western tufas, whose onset is at ca. 12 ka cal. BP with a maximum between 7 and 5 ka cal. BP. Afterwards,

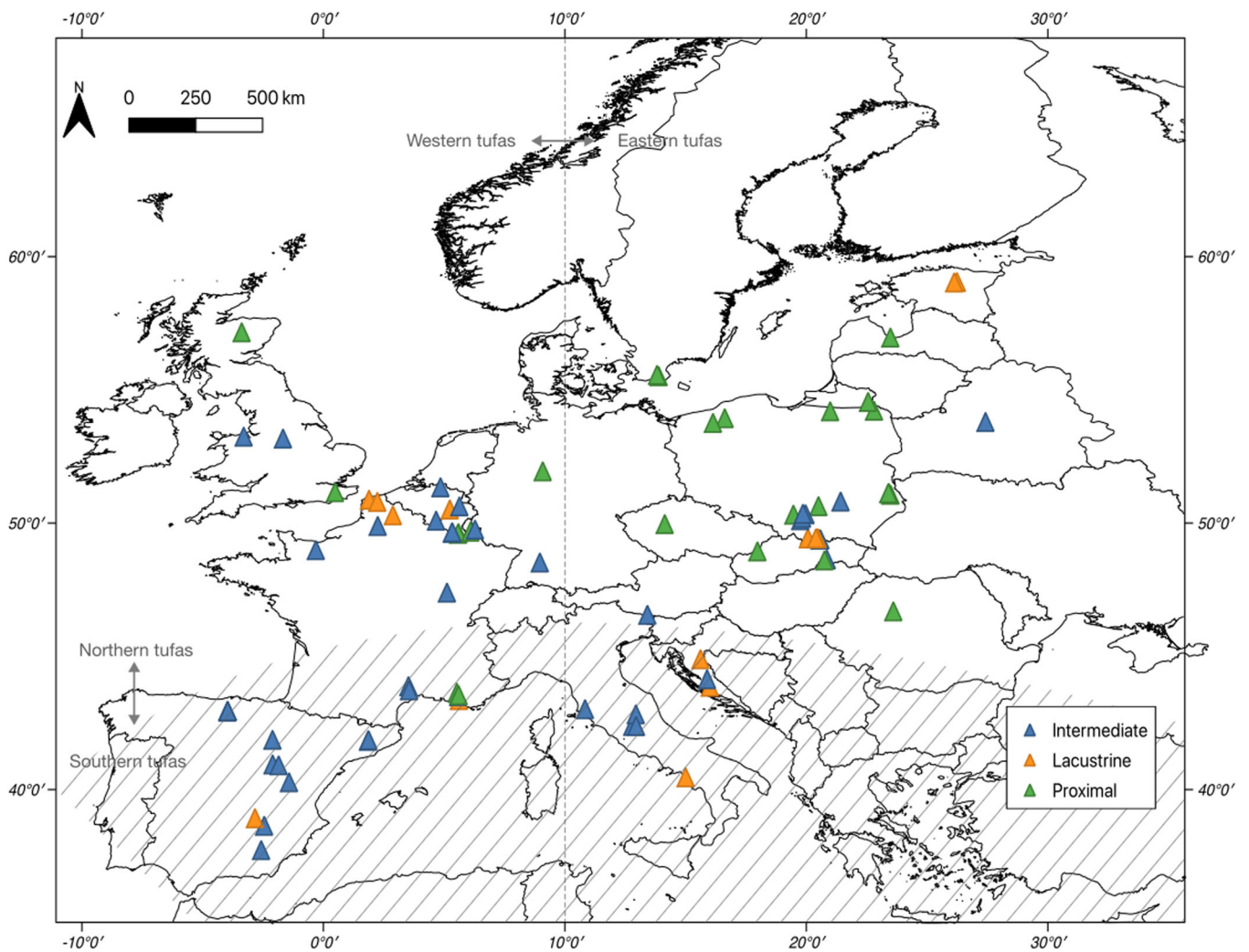


Figure 1. Map of all inventoried sites across Europe showing their type (intermediate, proximal, lacustrine) and allocation to the west/east and north/south groups (see Table 1 and text for details). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

the tufas show a relative decline from ca. 6 ka cal. BP in the east and ca. 5 ka cal. BP in the west. A similar time lag between the east and the west is observed when only fluvial tufas are considered. However, the amplitude and rate of change in the number of tufas are similar between eastern and western Europe, especially with respect to the Late Holocene decline, either for all or fluvial-only deposits (Fig. 3).

North/south comparisons

The following north–south comparisons separate tufas from the Mediterranean area (i.e. Spain, south-eastern France, Italy, Croatia; $n=28$) from those from the rest of Europe ($n=54$; Fig. 1 and Table 2), which experience temperate, oceanic to continental climates. The interest of the scientific community in tufa deposits in the mid-latitudes of Europe dates back further, especially in England, northern France, Belgium and Poland, as reflected by a greater number of publications since the 1970s (Table 1). This explains why two thirds of the inventoried sites are from temperate Europe (Table 2). In the Mediterranean area, fluvial deposits predominate in regional surveys (especially from Spain and south-eastern France; González Martín and González-Amuchastegui, 2014; González-Amuchastegui and Serrano, 2015b, 2015a; Ollivier et al., 2006; Vaudour, 1994), which partly explains why three quarters of the southern sites are riverine tufas (Table 2).

Figure 4 shows the temporal distribution of tufas from the Mediterranean area compared with that of deposits from

mid-latitudes in Europe (so-called ‘south’ and ‘north’, respectively). While the east–west differences were relatively small, significant discrepancies are observed between Mediterranean and mid-latitude tufas in both their development and decline, whether all or only fluvial deposits are considered: the onset, maximum and relative decline of tufa deposits are delayed by several thousand years in the south.

In the temperate mid-latitudes, tufas start to develop during the Lateglacial, then their number increases rapidly from ca. 12 ka cal. BP to reach a maximum around 10–9 ka cal. BP up to ca. 6 ka cal. BP. However, this relatively long phase of maximum development is interrupted by a short and slight decrease in the number of sites at the Early–Middle Holocene transition (ca. 8.5–8 ka cal. BP), both for all and fluvial-only deposits (Fig. 4). Thereafter, tufas from the European mid-latitudes show a rapid decline between 6 and 4 ka cal. BP, driven by the strong decrease in the number of fluvial deposits, which almost disappear around 2.5 ka cal. BP.

It is only after 10 ka cal. BP that tufas develop significantly in southern Europe, and their number gradually increases to a maximum between ca. 6.5 and 4 ka cal. BP, at the same time as the decline observed in the mid-latitudes (Fig. 4). In the Mediterranean area, the tufa decline is less pronounced than in any other part of Europe, even though fluvial deposits have been predominantly inventoried in this region (Table 2), and it occurs significantly later: only half of the (fluvial) tufas stopped depositing between ca. 4 and 2 ka cal. BP (Fig. 4).

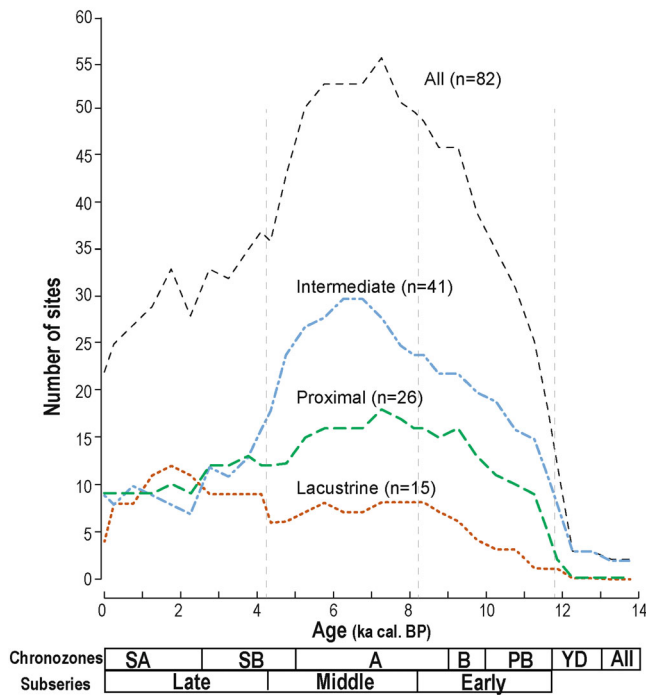


Figure 2. Evolution of the number of all, intermediate, proximal and lacustrine tufas during the Lateglacial and the Holocene (from 14 ka cal. BP), modified after Dabkowski (2020) by including 19 additional sites (Table 1). Abbreviations: All, Allerod; YD, Younger Dryas; PB, Preboreal; B, Boreal; A, Atlantic; SB, Subboreal; SA, Subatlantic. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. West–east and north–south distribution of all inventoried tufas and of fluvial deposits only.

	West	East	North	South
All tufas ($n = 82$)	41	41	54	28
Fluvial only ($n = 41$)	27	14	20	21

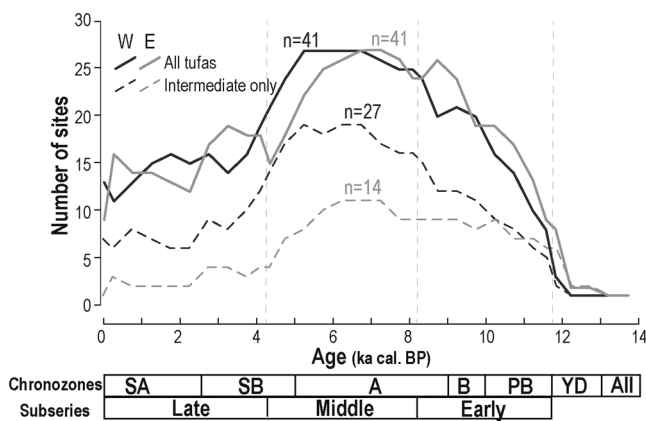


Figure 3. Evolution of the number of western (W: dark line) and eastern (E: grey line) tufas during the Lateglacial and the Holocene (solid line: all sites; dashed line: fluvial deposits). Abbreviations: All, Allerod; YD, Younger Dryas; PB, Preboreal; B, Boreal; A, Atlantic; SB, Subboreal; SA, Subatlantic.

Discussion

Most of the changes (either increases or decreases) observed in the number of tufa deposits are mainly driven by changes in the number of the fluvial ones in all considered areas (Figs. 3 and 4). This emphasises that riverine tufas are more sensitive to environmental changes, whether induced by climate or human

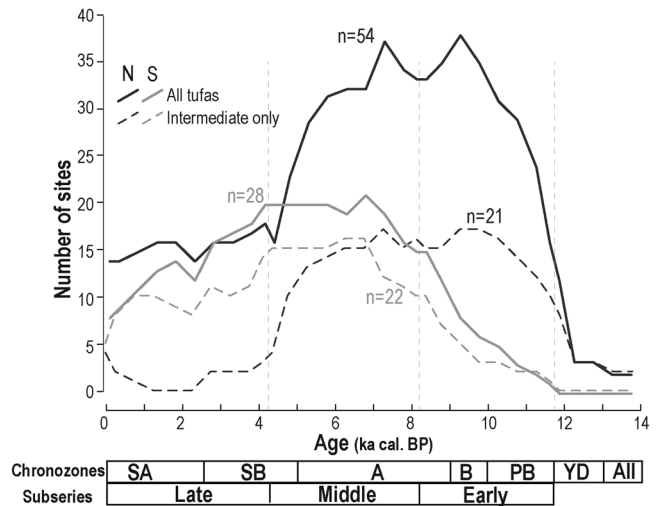


Figure 4. Evolution of the number of mid-latitude (so-called northern; N: dark line) and Mediterranean (i.e. southern; S: grey line) tufas during the Lateglacial and the Holocene (solid line: all sites; dashed line: fluvial deposits). Abbreviations: All, Allerod; YD, Younger Dryas; PB, Preboreal; B, Boreal; A, Atlantic; SB, Subboreal; SA, Subatlantic.

activities, than proximal (spring) or lacustrine tufas (Dabkowski, 2020). Therefore, only fluvial deposits are mapped in Fig. 5, where their distribution during the different Holocene sub-series is shown (Early, Middle and Late Holocene according to Walker et al., 2018 and Walker et al., 2012).

An unequal onset from the Lateglacial to the Middle Holocene

The earliest tufas appear during the Lateglacial, before they develop more rapidly during the Early Holocene in the north and especially in the north-east (Figs. 3 and 4). Thus, most of the known sites from this period are in England, Belgium–Luxembourg and Poland, while none are recorded in the south-west, e.g. in the Iberian Peninsula (Fig. 5). This uneven distribution probably reflects differences in the timing and intensity of the climatic improvement across Europe during the first half of the Holocene.

Quantified reconstructions of the European climate variability from 12 ka cal. BP, based on palynological data, show that mean annual temperatures increased more rapidly at the beginning of the Holocene in north-eastern Europe, where they exceeded pre-industrial values from ca. 8.5–8 ka cal. BP (Davis et al., 2003), even though colder conditions may persist locally in areas close to the remaining Scandinavian ice sheet (Lauterbach et al., 2010). In the west, temperatures did not reach pre-industrial values until ca. 6.5–6 ka cal. BP (Davis et al., 2003). Furthermore, speleothem records show that western Europe experienced cooler conditions than the east at the beginning of the Holocene (McDermott et al., 1999). In addition, a strong decoupling between Mediterranean and mid-latitude climate records is observed: while temperatures increased rapidly in temperate Europe during the Early Holocene, the Mediterranean region experienced a much more gradual warming throughout the Holocene (Davis et al., 2003; Lionello, 2012; Mauri et al., 2015; McDermott et al., 1999; New et al., 2000). These differences in the spatial dynamics of the warming from 12 ka cal. BP partly explain the dephasing of the onset and maximum of tufa development across Europe. In particular, the large north–south time lag (Fig. 4) is consistent with an earlier and stronger warming of the European mid-latitudes compared with the Mediterranean region.

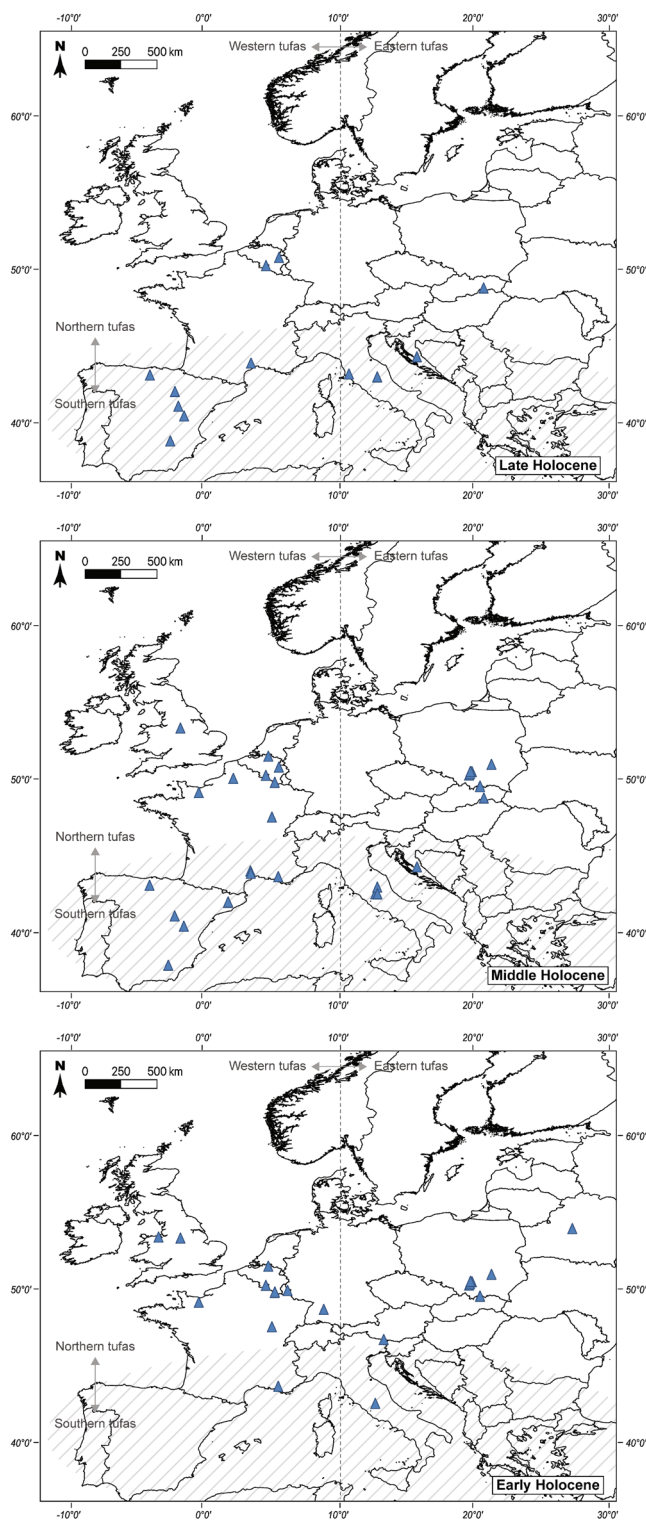


Figure 5. Maps of the inventoried European fluvial tufas during the Early, Middle and Late Holocene. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

However, tufa growth (apart from any anthropogenic disturbance) is mainly influenced by the presence of water and thus by rainfall/aridity conditions (Capezzuoli et al., 2014; Pentecost, 2005). Pollen-based reconstructions of mean annual (and seasonal) precipitation in Europe show that the beginning of the Holocene (12–10 ka cal. BP) was characterised by dry conditions throughout Europe, which persisted until ca. 9 ka cal. BP, depending on the region (Mauri et al., 2015): Poland became wetter from 11 ka cal. BP, then wet conditions extended to central Europe around 8 ka cal. BP and to the south(west)

around 7 ka cal. BP. The wettest period was between 7 and 6 ka cal. BP for the whole of Europe. These data are consistent with a slightly earlier development of tufas in eastern than in western Europe (Fig. 3) and with the wider distribution of inventoried tufa sites across Europe during the Middle Holocene (Fig. 5). Water availability can be further assessed by the precipitation minus evaporation (P-E) ratio, also reconstructed from palynological data (Mauri et al., 2015). It indicates conditions of low moisture across the whole of Europe at the beginning of the Holocene (around 12–11 ka cal. BP), before a rapid establishment of a west–east gradient between 10 and 7 ka cal. BP, with drier conditions in south-western Europe and increased water availability in the north-east. In particular, the western Mediterranean area (i.e. Spain and south-eastern France) is characterised by drier conditions throughout the Holocene, both in terms of precipitation and water availability (P-E ratio), and by a weak humidity maximum that was reached later than in the north, ca. 5 ka cal. BP. These contrasting moisture conditions are coherent with the time lag observed in the tufa development and the maximum between the mid-latitudes and the Mediterranean region (Fig. 4).

Regional climatic characteristics also result in the variability of the post-glacial afforestation of Europe, while the human influence on vegetation is assumed to be small (Behre, 1988): the forest cover expanded rapidly from southern, eastern and central Europe refugial areas to the north and especially to the west, and its maximum expansion is generally recorded between 8.5 and 6 ka BP (Brewer et al., 2002; Fyfe et al., 2015; Zanon et al., 2018), coinciding with the wettest period and the maximum number of tufa deposits. In addition, only a slight increase in the forest cover density has been reported for the Mediterranean region from the Lateglacial to the Middle Holocene (Zanon et al., 2018), which may be due to the combined effects of aridity, landscape heterogeneity, and the complex distribution and composition of the preceding glacial forests, especially in Spain (Carrión et al., 2010; Gil-Romera et al., 2009), where most of the southern tufas have been inventoried and show a slow and delayed onset compared with mid-latitude sites (Fig. 4).

The marked differences in the timing and amplitude of the onset and maximum of tufa deposition during the first half of the Holocene are therefore strongly dependent on the climatic discrepancies across Europe, especially in terms of precipitation and humidity, and the resulting vegetation cover. This is consistent with previous studies that have highlighted the important role of water availability for tufa development, even under cool conditions, and the relationship between tufa deposition and forest density (Dramis et al., 2014; Ford and Pedley, 1996; Garnett et al., 2006; Goudie et al., 1993; Martín-Algarra et al., 2003).

Possible effect of the 8.2 event

A brief decrease in the number of ‘northern’ tufas is observed (Fig. 4) between 8.5 and 8 ka cal. BP, a time that corresponds to the ‘8.2 event’. It is recognised in numerous records, especially continental ones, in Europe (Giesecke et al., 2011; Griffiths and Robinson, 2018; Magny et al., 2003; Prasad et al., 2009; Tinner and Lotter, 2001) and worldwide (Rohling and Pälike, 2005; Walker et al., 2018; Walker et al., 2012), and is considered to be one of the most abrupt climatic changes during the Holocene (Alley and Agustsdottir, 2005; Thomas et al., 2007). In Europe, the 8.2 event corresponds to a phase of pronounced cooling lasting 400 to 600 years, beginning around 8.6 ka cal. BP (Alley and Agustsdottir, 2005; Rohling and Pälike, 2005; von Grafenstein et al., 1998). In terms of humidity, contrasting responses are recorded in Europe where

conditions are generally drier, but a central European zone influenced by the westerlies (roughly between 40° N and 50° N) may experience increasing humidity (Magny et al., 2003).

Thus, the marked cooling that constitutes the 8.2 event and the associated drier conditions above 50° N may explain the decrease in tufas in the northern half of Europe that is observed during the same period. However, it is surprising that the cooler and especially drier conditions experienced around the Mediterranean did not also lead to a reduction in the number of tufas in this region (Fig. 4). In contrast to other variations in tufa development discussed previously, changes contemporaneous with the 8.2 event are not particularly evident in fluvial deposits (Fig. 4), whereas proximal (spring) deposits show a decrease at this time. The relatively small number of Mediterranean tufas inventoried here, which are mostly fluvial (Table 2), could explain why no decrease in their number is observed at the Early to Middle Holocene transition (i.e. the 8.2 event).

Furthermore, this compilation discusses the presence/absence of tufa without considering their rate of development or the changes in their sedimentological characteristics. However, relatively short climatic changes, such as the 8.2 event, are more likely to be associated with, for example, hiatuses, reduced sedimentation rates, increases in organic matter or detrital deposits, but not with a complete cease in tufa deposition. For instance, cooler and drier conditions were recorded around 8.5–8 ka cal. BP in the isotopic record of the Holocene tufa sequence at Mituchovci (Slovakia), within peaty deposits with a lower sedimentation rate than the typical tufa facies that comprises most of the sequence (Dabkowski et al., 2019). Precisely dated sites, where age–depth models are available, that are well documented in terms of stratigraphy and sedimentology, and that can also provide palaeoclimatic records, are needed to further discuss the impact of the 8.2 event on tufas across Europe.

The Late Holocene tufa decline, a mid-latitude story?

Between 6 and 4 ka cal. BP, the tufa decline is particularly pronounced in the European mid-latitudes and occurs later and to a lesser extent in the Mediterranean area (Fig. 4), where most tufas are inventoried during the Late Holocene (Fig. 5). Conversely, there is little difference in the west/east timing and amplitude of this decline (Fig. 3).

The strong link between tufa development and climate has been shown above. Therefore, a decrease in the number of tufa deposits might be expected as temperatures lowered after the Atlantic Thermal Maximum. However, the temperature decrease was smaller than the amplitude of the warming at the beginning of the Holocene, except in north-eastern Europe, while a continuous warming is even reported for south-western Europe (Davis et al., 2003; Mauri et al., 2015; Kaufman et al., 2020). This temperature pattern may partly explain the geographical distribution of European tufas during the Late Holocene (Fig. 5), but climatic conditions (both temperature and precipitation) remained suitable for tufa formation throughout Europe (Mauri et al., 2015; McDermott et al., 2011). As previously suggested, human practices may have had a variable but dominant effect on tufa deposition during the Late Holocene. In particular, deforestation may have had numerous effects at the regional scale, including (1) changes in (ground)water chemistry caused by soil erosion and leaching or by the reduction of root respiration and leaf fall, (2) changes in shade and temperature conditions, (3) the supply of material initiating dams and (4) erosion processes (Dabkowski, 2020; Goudie et al., 1993; Pentecost, 1995).

Anthropogenic effects on the environments have been detected throughout Europe since the beginning of the neolithisation, although natural climatic changes may also have played a role (Kaplan et al., 2009; Marquer et al., 2017; Ruddiman et al., 2016). Models using palynological data suggest a more intense and rapid deforestation after ca. 6 ka cal. BP in mid-latitude Europe than in the far north (Scandinavia) and the Mediterranean region (Carrión et al., 2010; Fyfe et al., 2015; Marquer et al., 2014; Zanon et al., 2018). This corresponds to the most favourable zone for the development of agriculture and livestock, according to the pre-industrial climatic conditions and soil quality (Kaplan et al., 2009; Ramankutty et al., 2002). The intensification of deforestation is also well identified in local to regional pollen records (Carrión et al., 2007; Fyfe et al., 2015; Gil-Romera et al., 2009; Whitehouse et al., 2014; Woodbridge et al., 2014). However, the apparently weaker and more gradual decrease of forested environments in the Mediterranean area may actually reflect the fact that landscapes in this area were already largely open during the Early/Middle Holocene (Carrión et al., 2010; Zanon et al., 2018). These observations suggest that, on a regional scale, deforestation might be the anthropogenic change that most affects the development of tufa.

Conclusions

Our observations resulting from this new updated compilation, which cross-references the chronological and spatial distribution of European tufas since 14 ka cal. BP, re-emphasise the close relationship between tufa development and environmental changes. Most variations in the number of tufas are driven by changes in the number of fluvial deposits, not only during the Late Holocene decline, confirming that riverine tufas are more sensitive to both climatic and environmental changes. These variations show spatial differences in both timing and amplitude.

The strongest discrepancies are observed between the Mediterranean area and the rest of Europe, which reflects the important climatic decoupling of these regions: the onset and maximum of tufa deposition are delayed by several thousand years in the south. The Late Holocene tufa decline also occurred later in the Mediterranean region and was much less pronounced than in the mid-latitudes, due to drier conditions and associated human practices (e.g. less-intensive deforestation).

At mid-latitudes, the onset and maximum of tufa development show a spatial variability that reflects an east–west gradient, in terms of temperature but especially humidity, in the improvement of climatic conditions during the first half of the Holocene. The brief climatic cooling of the 8.2 event also seems to affect tufa development, but more detailed data, particularly in terms of chronology and stratigraphy/sedimentology, are needed to discuss this further.

Finally, the Late Holocene tufa decline is well marked in the European mid-latitudes, where it started slightly earlier in the east than in the west. During the Late Holocene, climate variability was weak throughout Europe (with the exception of the Mediterranean region). The growing impact of human practices is more likely to explain the tufa decline and the regional differences in its timing and amplitude, especially the speed and intensity of deforestation. However, a regional synthesis coupling archaeological data and palaeoenvironmental reconstructions is still needed to understand in detail, and especially on a centennial to decadal timescale, the relationship between the tufa decline and anthropogenic changes, as other mechanisms may be involved (Dabkowski, 2020; Goudie et al., 1993).

Acknowledgements. We thank both anonymous reviewers and the review editor, Achim Brauer, for their constructive comments on the manuscript.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Abbreviation. ka cal. BP, thousand calibrated years before present.

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